Total Maximum Daily Load
Selenium in North San Francisco Bay

Draft Staff Report
For Proposed Basin Plan Amendment

Prepared by Barbara Baginska

California Regional Water Quality Control Board
San Francisco Bay Region

July 24, 2015

San Francisco Bay Regional Water Quality Control Board
1515 Clay Street, Suite 1400
Oakland, CA 94612
Phone: 510-622-2300
Fax: 510-622-2460
http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

TABLE OF CONTENTS

1 INTRODUCTION 1

2 PROBLEM STATEMENT 0

2.1 Basis for 303(d) Impairment Listing 0

2.2 Project Objectives 3

3 BACKGROUND AND IMPAIRMENT ASSESSMENT 4

3.1 Environmental Setting 4

3.2 Characteristics, Speciation and Environmental Fate 5

Properties and Distribution in the Environment 6

3.3 Ambient Selenium Levels in the North Bay 7

3.4 Existing Water Column Objectives 13

3.5 Human Health Criteria 14

3.6 Selenium Bioaccumulation and Impact on Aquatic Life 16

3.7 Toxicity and Selenium Related Risks for Fish and Birds 17

Initial Screening of Available Toxicity Studies 18

Selenium Toxicity Thresholds for North Bay Fish 20

White sturgeon 20

Sacramento splittail 25

Chinook salmon 26

Toxicity Mitigating Conditions 27

Evaluation of Selenium Impairment in Birds 28

Clapper rail 31

Surf scoter and Greater/Lesser scaup 32

4 NUMERIC TARGETS 36

4.1 Fish Tissue-Based Numeric Targets 36

4.2 Water Column Target 38

Derivation of Allowable Water Column Concentrations 38

Sturgeon Food Web and Trophic Transfer Factors 41

Partitioning Coefficients (K_ds) 43

Calculation of the Allowable Dissolved Selenium Concentration 46

5 SOURCE ANALYSIS – SOURCES AND LOADS 49

5.1 Selenium Sources 51

Municipal and Industrial Wastewater Dischargers 51

North Bay Petroleum Refineries 51

Municipal Wastewater Dischargers 55

Industrial Wastewater Dischargers 59

Urban and Non-Urban Runoff from Local Tributaries 59

Load Estimates Using Simple Model with All Data (Method 1) 62

Load Estimates Using Available Measured Flow and SWAMP Data (Method 2) 64

Land Use-Specific Loads with Modeled Runoff and Concentration Data from BASMAA and SWAMP Studies (Method 3) 66

Loads from San Joaquin and Sacramento Rivers Delivered via Delta 69

Direct Atmospheric Deposition 75

5.2 Erosion and Transformations in Bottom Sediments 76

6 LINKAGE ANALYSIS – RELATIONSHIP BETWEEN SOURCES, TARGETS AND BENEFICIAL USES 78
6.1 Importance of Particulate Selenium in Managing Ecological Exposure 78
6.2 Modeling Framework 81
ECoS3 Estuary Model 82
DYMBAM Bioaccumulation Model 86
Model Calibration and Evaluation 87
6.3 Effects of Load Change 90
Point and Non-Point Load Change Scenarios 90
Background Conditions 92
6.4 Predicted Concentrations in Bivalves 94
6.5 Assimilative Capacity 96
7 TMDL, LOAD ALLOCATIONS, AND MARGIN OF SAFETY 102
7.1 Wasteload Allocations 103
North Bay Petroleum Refineries 103
Municipal Wastewater and Small Industrial Dischargers 103
7.2 Load Allocations 106
7.3 Margin of Safety and Seasonal Conditions 107
8 IMPLEMENTATION PLAN 109
8.1 Internal and External Sources 109
Petroleum Refineries 109
Effluent Limit Calculation Approach 110
Municipal and Small Industrial Dischargers 111
Central Valley Watershed 111
Local Tributaries 114
Atmospheric Deposition 114
8.2 Relevant Monitoring and Special Studies 114
8.3 Adaptive Implementation 116
9 REGULATORY ANALYSES 117
9.1 CEQA Analysis 117
9.2 Environmental Checklist 118
9.3 Consideration of Alternatives 131
Alternative: No Project 132
Preferred Alternative 132
9.4 Economic Considerations 132
10 REFERENCES 134
APPENDIX A DRAFT PROPOSED BASIN PLAN AMENDMENT 147

FIGURES

Figure 1: Segments of San Francisco Bay 1
Figure 2: Locations of RMP long-term monitoring sites and sites sampled in 1999 8
Figure 3: Total selenium concentrations at RMP monitoring sites for the period of 2005-10 9
Figure 4: Speciation of dissolved selenium in North Bay and main tributaries 10
Figure 5: Distribution of dissolved selenium along the salinity gradient for different flow conditions. 11
Figure 6: Distribution of particulate selenium along the salinity gradient for different flow conditions 12
Figure 7: Selenium concentrations in sport fish species in San Francisco Bay in 2009 15
Figure 8: Conceptual representation of selenium biomagnification in North Bay 17
Figure 9: Selenium concentrations in selected fish at which adverse effects may occur 19
Figure 10: Occurrence of edema and/or skeletal deformities in the larvae from eggs of white sturgeon exposed to dietary selenium. 22
Figure 11: Observed selenium concentrations in white sturgeon in San Francisco Bay 24
Figure 12: Observed range of dietary selenium at which adverse effects in birds may occur 30
Figure 13: Concentrations of selenium in bird eggs 31
Figure 14: Selenium muscle tissue concentration in diving ducks from San Francisco Bay 33
Figure 15: Simplified diagram of components in ecosystem-scale selenium modeling 39
Figure 16: Changing mix of particulate selenium from the Delta to the Golden Gate 44
Figure 17: Focused seaward locations for October 2011 transect 45
Figure 18: Variability in estimated K_ds in Suisun Bay and Carquinez Strait 45
Figure 19: Locations and indicative loads from point sources 51
Figure 20: Load reductions and selenium composition in petroleum refinery effluents 52
Figure 21: Effluent selenium concentrations in Chevron and Valero refineries 53
Figure 22: Dry and wet season selenium loads from refineries from 2008 through 2012 54
Figure 23: Total particulate selenium concentration in petroleum refinery effluents 55
Figure 24: Total selenium concentrations in effluent from selected largest municipal dischargers 56
Figure 25: Hydrological areas surrounding the North Bay 60
Figure 26: Average long-term monthly selenium loads at selected gauging locations 65
Figure 27: Comparison of load estimates from local tributaries using different calculation methods 69
Figure 28: Water balance in the Delta for an average flow year 2000 70
Figure 29: Estimates of dry and wet season riverine loads 71
Figure 30: Locations of DSM2 model outputs 72
Figure 31: Loads of dissolved selenium from Sacramento and San Joaquin watersheds by water year 73
Figure 32: Conceptual model showing selenium biotransformations and implications for a benthic bivalve-based food web (*left panel*) and a water column food web (*right panel*) 79
Figure 33: Selenium enrichment and trophic transfer in aquatic food web 80
Figure 34: Schematic representation of the modeling framework linking selenium in water column and suspended particulates to bivalves, and then to predator species 81

Figure 35: Spatial location of 33 model segments (*red dots*) and schematic representation of the estuary showing boundary conditions and point source inputs 83
Figure 36: Interactions and transformations of dissolved and particulate selenium between different compartments in each cell of the ECoS3 model 85
Figure 37: Predicted selenium concentrations for different loading scenarios..................................91
Figure 38: Model-predicted selenium concentrations in bivalves under natural background loads and with point source loads..93
Figure 39: Selenium concentrations (Cmss) in *C. amurensis* simulated with different biodynamic parameters 94
Figure 40: Simulated selenium concentrations in bivalve *C. amurensis* compared to long-term data from USGS at Carquinez Strait (1995-2010) 95
Figure 41: Annual fluxes of total selenium simulated for dry and wet months of 1998 - 2013...........98
Figure 42: Simulated distribution and uptake of selenium by phytoplankton 99
Figure 43: 2010-2011 dry weather total particulate selenium across the estuary and receiving water concentrations near the five refinery outfalls 100
Figure 44: Minimum, maximum and average dissolved selenium concentrations during dry and wet seasons near refinery outfalls 100
Figure 45: Selenium discharge and targets for the Grassland Drainage Area 113

TABLES

Table 1: The North Bay segments listed as impaired by selenium 2
Table 2: Beneficial uses of the North Bay potentially impaired by selenium.......................................3
Table 3: Water quality criteria for selenium in Bays and Estuaries...13
Table 4: Selenium effect level concentrations estimated for white sturgeon 23
Table 5: Proposed numeric targets for selenium in the North San Francisco Bay 36
Table 6: Literature-based TTFs for *C. amurensis* 42
Table 7: Summary of parameters for translation of TMDL tissue target to water column concentration 47
Table 8: Water column concentrations protective of clam eating fish...47
Table 9: Sources and loads of selenium in the North Bay 50
Table 10: Summary statistics of treated effluent from petroleum refineries......................................52
Table 11: Summary statistics of selenium concentrations in municipal wastewater effluent.............57
Table 12: Average annual selenium loads from municipal wastewater dischargers..........................58
Table 13: Estimated selenium loads from industrial wastewater dischargers in the North Bay.........59
Table 14: Selenium concentrations at downstream locations by season 61
Table 15: Runoff and selenium loads from local watersheds..63
Table 16: Summary of selenium loads at the USGS gauging stations 65
Table 17: Estimated wet and dry season loads from local tributaries (*Method 2*) 66
Table 18: Land use specific runoff coefficients and mean selenium concentrations 67

Table 19: Loads derived from land use composition in local tributaries ... 68

Table 20: Dry and wet season loads to the North Bay from the Central Valley watershed and tributaries ... 74

Table 21: Parameters for DYMBAM model ... 87

Table 22: Testing performed to assess model performance ... 89

Table 23: Simulated particulate selenium concentrations for existing and natural load conditions ... 93

Table 24: North Bay TMDL and load and wasteload allocations ... 102

Table 25: Proposed wasteload allocations for petroleum refineries ... 103

Table 26: Proposed wasteload allocations for municipal and industrial discharges ... 104

Table 27: Average percentages (±stdev) of dissolved and particulate selenium fraction in effluent from municipal facilities ... 105

Table 28: Preliminary estimates of performance-based numeric effluent limits based on 95th percentile of daily loads (2000-2012) ... 110

1 INTRODUCTION

This Staff Report presents the supporting documentation for a proposed Basin Plan amendment to establish a Total Maximum Daily Load (TMDL) and implementation plan for selenium in the North San Francisco Bay segments (North Bay) including a portion of Sacramento/San Joaquin Delta, Suisun Bay, Carquinez Strait, San Pablo Bay and Central Bay (Figure 1). The TMDL is based on attainment of a water column and fish tissue target concentration protective of human health, aquatic life, and wildlife.

Section 303(d) of the federal Clean Water Act (CWA) requires that States identify water bodies - bays, rivers, streams, creeks, and coastal areas - that do not meet water quality standards and identify the pollutants that cause the impairment. The North Bay appears on the 2010 303(d) list because selenium was identified as causing an impairment of the Bay's existing beneficial uses, including estuarine habitat, preservation of rare and endangered species, and sport fishing. For these 303(d) listed waters, states are required to establish a TMDL for the pollutant responsible for the impairment. The purpose of a TMDL is to devise a strategy to attain water quality objectives, and restore and protect the beneficial uses of an impaired water body.

A TMDL is defined as the "sum of the individual waste load allocations for point sources and load allocations for non-point sources and natural background," such that the capacity of the water body to assimilate pollutant loadings is not exceeded. TMDLs are required to account for seasonal variations, and must include a margin of safety to address uncertainty in the analyses.

In addition, the scientific basis of the Basin Plan amendment is currently in the process of external scientific peer review. This step is required under section 57004 of the Health and Safety Code, which specifies that an external review is required for work products that serve as the basis for a rule, "…establishing a regulatory level, standard, or other requirements for the protection of public health or the environment." All comments by the peer reviewer(s) will be considered in finalizing this staff report and the proposed Basin Plan amendment.

The process of establishing a TMDL includes compiling and considering available data and information, conducting scientific analyses relevant to the impairment problem, identifying sources, and, if necessary, allocating responsibility for actions to address the impairment. This report is organized into sections that reflect background information as well as the key elements of the TMDL process. Section 2 presents the problem definition and the objectives of the project. Section 3 provides background information on characteristics, speciation and environmental fate of selenium as well as the existing water quality objectives and assessment of selenium bioaccumulation in fish and birds. Section 4 establishes the numeric targets for the TMDL expressed as fish-tissue and water column concentrations protective of the most sensitive species. The main sources and estimates of the loads of selenium are discussed in Section 5. Section 6 explains the key processes and conditions leading to selenium bioaccumulation in the North Bay and linkages between the sources, loads, and the proposed targets. The recommended selenium allocations and the plan to implement the allocations are presented in Section 7 and 8, together with the monitoring activities proposed to ensure that the targets are met and the beneficial uses are protected. Finally, Section 10, References, lists all the information sources cited and relied upon in the preparation of this Staff Report.

The proposed Basin Plan Amendment is included in Appendix A.

2 PROBLEM STATEMENT

North San Francisco Bay is listed as impaired for selenium because bioaccumulation of this element led to recurring health advisories for local hunters against consumption of diving ducks. Moreover, elevated selenium concentrations found in biota exceed levels associated with potential reproductive impacts in fish elsewhere.

The introduction of the Asian clam (*Corbula amurensis*)[1] into the Bay in 1986 has exacerbated the bioaccumulation of selenium in benthic fish. This non-native clam is a prodigious filter-feeder, and by consuming large quantities of selenium-laden particles this exotic species provides a pathway for biotransformation of a considerable mass of selenium from the benthic food web to diving ducks and large fishes such as white sturgeon. The estimated selenium concentrations found in sturgeon's muscle sporadically exceed the draft United States Environmental Protection Agency (USEPA) limit of 11.8 µg/g proposed for freshwater fish (USEPA 2014). Increased levels of selenium in the Bay-Delta have been suggested as a possible contributing factor to the observed decline of some key species, (e.g. white sturgeon, Sacramento splittail, and diving ducks) and therefore these species are the main focus of the analyses in this report.

This TMDL addresses the selenium impairment in the North San Francisco Bay segments, which for the purpose of this project include a portion of the Sacramento/San Joaquin Delta (within the San Francisco Bay region), Suisun Bay, Carquinez Strait, San Pablo Bay and Central Bay (Figure 1).

2.1 Basis for 303(d) Impairment Listing

In 1987, the California Department of Health Services issued a human health advisory against consumption of two species of ducks (Greater scaups and Surf scoters) from the Bay-Delta area due to elevated concentrations of selenium in tissue of the waterfowl. The health advisory was based on the initial results reported by the selenium Verification Study that began in 1985 (DFG 1991). This advisory reflected the selenium impairment of San Francisco Bay and provided a basis for placing the Bay on the 303(d) list of impaired water bodies.

The purpose of the Verification Study was to provide a comprehensive assessment of selenium and trace elements in a wide array of aquatic and terrestrial organisms from

[1] Also known as *Potamocorbula amurensis*

previously identified areas of concern. The selenium contamination was measured in 26 locations throughout the state including the areas in the San Francisco Bay and the Delta. The results of the study showed very high concentrations of selenium in scoters (more than 30 µg/g wet weight in liver) as well as elevated levels of selenium in the muscle tissue of white sturgeon (average of 4.1 µg/g wet weight or >16 µg/g dry weight). The levels of selenium in scoters were higher than those determined by the US Fish and Wildlife Services (USFWS) to cause selenium toxicosis and reproductive impairment.

Figure 1: Segments of San Francisco Bay

The study also found high concentrations of selenium in clams and other animals that are a source of food for these migratory waterfowl and certain larger fishes. As an example, on average, selenium concentrations in the muscle of white sturgeon, which feeds primarily on benthic organisms, were five times higher than in striped bass, which are primarily piscivorous. The study concluded that food habits played a role in selenium bioaccumulation, and that the species with elevated levels of selenium in their tissue were either bottom-dwellers or species with diets comprising of benthic organisms.

As a result, the San Francisco Bay segments were initially identified as impaired by selenium in the 1998 303(d) list (Table 1). Among others, the listing factors include a health advisory against consumption of edible resident organisms and bioaccumulation of pollutants in tissue of aquatic life.

Table 1: The North Bay segments listed as impaired by selenium

North San Francisco Bay segment	2010 303(d)List	Indicator of Impairment
Portion of Sacramento-San Joaquin Delta	✓	Hatchability in nesting diving birds Health consumption advisory in effect for scaup and scoter (diving ducks)
Suisun Bay	✓	
Carquinez Strait	✓	
San Pablo Bay	✓	
Central San Francisco Bay	✓	

While water column selenium concentrations in the North Bay do not exceed the National Toxics Rule chronic criterion for protection of aquatic life (5 µg/L), the observed bioaccumulation of selenium in fish is the basis of impairment of the estuarine habitat (EST) and could pose a threat to other estuarine organisms including waterfowl and shorebirds. Other designated uses of the Bay, such as preservation of rare and endangered species (RARE) as well as commercial and sport fishing (COMM) could also be affected by selenium. These beneficial uses are described in Table 2.

Since the early 1990s the Water Board has undertaken actions to better understand conditions leading to selenium bioaccumulation in aquatic life, and to alleviate selenium impairment in the North Bay. In particular, petroleum refineries investigated selenium sources within the plants and evaluated potential waste reductions measures. As a result the loads of selenium discharged by petroleum refineries were reduced by more than 75 percent, and technological improvements in the treatment of wastewater led to more effective removal of the most bioavailable forms of selenium (selenite) from effluent before it reaches the Bay.

2.2 Project Objectives

The proposed project is intended to evaluate the contributions of the existing and future selenium discharges to the impairment of beneficial uses in the North San Francisco Bay associated with controllable water quality factors (i.e. resulting from human activities that can influence water quality and can be reasonably controlled through prevention, mitigation, or restoration actions). The specific goals are:

- Comply with the CWA requirement to adopt a TMDL for Section 303(d)-listed water bodies;
- Protect the overall aquatic health and human health beneficial uses of the North Bay and enhance its aesthetic and recreational values;
- Establish numeric targets protective of North Bay beneficial uses;
- Determine selenium loads protective of North Bay beneficial uses; and
- Establish an approach for implementation that attains the TMDL.

Table 2: Beneficial uses of the North Bay potentially impaired by selenium

Designated Beneficial	Description
Estuarine Habitat (EST)	Uses of water that support estuarine ecosystems, including, but not limited to, preservation or enhancement of estuarine habitats, vegetation, fish, shellfish, or wildlife (e.g., estuarine mammals, waterfowl, shorebirds), and propagation, sustenance, and migration of estuarine organisms.
Preservation of Rare and Endangered Species (RARE)	Uses of waters that support habitats necessary for the survival and successful maintenance of plant or animal species established under the state and/or federal law as rare, threatened, or endangered.
Ocean, Commercial and Sport Fishing (COMM)	Uses of water for commercial or recreational collection of fish, shellfish, or other organisms in oceans, bays and estuaries, including, but not limited to, uses involving organisms intended for human consumption or bait purposes.

3 BACKGROUND AND IMPAIRMENT ASSESSMENT

3.1 Environmental Setting

San Francisco Bay, with an area of approximately 1,600 square miles, is the largest estuary on the West Coast. The region is recognized as having utmost ecological and economic importance. It supports a variety of natural habitats and a diverse wildlife population, and provides drinking water for more than 70 percent of Californians and irrigation water for 4.5 million acres of farmland. The North Bay, in particular, supports a diverse fish and bird population. The fish supported include both sport fish and threatened and endangered fish species. The five most common sport fish in the North Bay are: (SFEI 2000; listed in order of catch frequency):

- Striped bass (*Morone saxatilis*)
- Halibut (*Paralichthys californicus*)
- Jacksmelt (*Atherinopsis californiensis*)
- White sturgeon (*Acipenser transmontanus*)
- White croaker (*Genyonemus lineatus*)

In addition to the sport fish listed above, the North Bay supports the following threatened and endangered fishes (Beckon and Maurer 2008):

- Chinook salmon (*Oncorhynchus tshawytscha*)
- Delta smelt (*Hypomesus transpacificus*)
- Green sturgeon (*Acipenser medirostris*)
- Longfin smelt (*Spirinchus thaleichthys*)
- Sacramento perch (*Archoplites interruptus*)
- Sacramento splittail (*Pogonichthys macrolepidotus*)
- Steelhead trout (*Oncorhynchus mykiss*)
- Tidewater goby (*Eucyclogobius newberryi*)

The Bay is commonly divided into segments including Sacramento/San Joaquin Delta, Suisun Bay, Carquinez Strait, San Pablo Bay, Central Bay, and Lower and South Bay (Figure 1). Each segment has a distinct ecological structure defined by the local tidal datum, amount of fresh water influx, sediment input, and the underlying hydrology. The North Bay, which extends from the Sacramento/San Joaquin Delta through Central Bay, differs significantly from the South Bay as it receives almost 90percent of the entire fresh water and sediment inflow into the Bay (SFEP 1992).

The northward-flowing San Joaquin and southward-flowing Sacramento Rivers discharge into the northern reach of the Bay and carry about 60 percent of the state runoff, draining approximately 152,500 square kilometers or 40 percent of California's surface area (Conomos *et al*. 1985). The Sacramento River typically accounts for 80 percent of the fresh water inflow coming through the Delta into the Bay and the San Joaquin River for 15 percent. The presence of freshwater inflow into the North Bay causes stratification of Bay waters and generates horizontal salinity gradients. Salinity gradually increases from one part of salt per thousand (ppt) in the Delta to approximately 30 ppt near the mouth of the Bay (Cohen 2000). Tidal action, river flow and stratification that occur in the North Bay result in the average residence time being three to six times shorter than in the southern portion of the Bay.

Sacramento and San Joaquin Rivers are fundamental to the health of the shallow water habitats in the North Bay area; however, they also provide a conduit for selenium-rich drainage and agricultural runoff. Freshwater inflows from the Central Valley watershed are the major source of new sediment input into the Bay. Most new sediment (approximately 80 percent) originates in the Sacramento - San Joaquin River drainage and enters primarily as suspended load during the high winter flows. Much of the winter sediment load initially settles out in San Pablo Bay. During the low flow summer months, wind-generated waves and tidal currents re-suspend the previously deposited sediment and redistribute it over a wider area. Selenium affiliated with sediments is effectively mobilized and could enter into food webs contributing to long-term dietary exposure of fish and wildlife (Lemly 1999). Therefore sediment dynamics exerts an important control on the distribution, transport, and speciation of selenium in the Bay.

3.2 Characteristics, Speciation and Environmental Fate

Selenium is a naturally occurring trace element that is widely distributed but dispersed in the environment. It is commonly found in marine sedimentary rock formations and soils developed from parent seleniferous material.

At trace concentrations, selenium is an essential nutrient for plants and animals and it is important to human health. As a vital constituent of selenoproteins, selenium plays a significant role in production of thyroid hormones, in the functioning of immune system and in prevention of oxidative stress or inflammation (Rayman 2000). However, the margin between essential concentrations of selenium in diet of plants, animals or humans and the concentrations that can cause toxicity or poisoning is the smallest among all known micronutrients.

Properties and Distribution in the Environment

Selenium exists in a number of chemical forms and exhibits a complex biochemistry. Most common selenium species include: elemental selenium (Se^0), selenide (Se^{2-}), selenite Se^{4+}(SeO_3^{2-}), and selenate Se^{6+}(SeO_4^{2-}). Oxidation level is the key factor determining the fate of selenium in the environment. Concentration, speciation and partitioning of selenium in a given environment are mostly governed by complex interactions between pH and redox conditions, presence of metal oxides, and biological interactions (USDHHS 2003 Chapter 6). Selenomethionine (SeMet) is the major species (60-80 percent of total selenium) in consumer organisms such as benthic invertebrates, fish, and birds, and thus represents an important form of selenium in the environment (Fan *et al*. 2002, Janz *et al*. 2014). As described by Lemly (1997) the aquatic cycling of selenium includes four major pathways: 1) it can be absorbed or ingested by organisms, 2) it can bind or complex with particulate matter, 3) it can remain free in solution, or 4) it can be released to the atmosphere through volatilization.

Background selenium concentrations are typically below 1 µg/L, and often range from 0.1 to 0.4 µg/L in natural freshwater and estuarine ecosystems (Eisler 1985, Lemly 1997). Selenium concentrations in present-day seawater average approximately 0.09 µg/L (Hem 1985). Selenate and selenite are the most soluble and the most mobile forms of selenium that predominate in well-oxygenated, aerobic surface waters. Direct uptake of dissolved selenium from the water column by animals is slow and its contribution to bioaccumulation in aquatic organisms is negligible. However, out of these two common selenium species, selenite is more readily taken up by bacteria, which, in turn, serves as a path for rapid biotransformation into organoselenides. This biologically reduced selenium is then directly available to rooted plants, bottom-dwelling invertebrates and detrital-feeding fish and wildlife (Abu-Saba and Ogle 2005, Amweg *et al*. 2003).

Average concentrations of selenium found in sediments and soils usually range from 0.01 to 0.02 mg/kg with most seleniferous soils containing less than 2 mg/kg (USDHHS 2003, Chapter 6). However, Cretaceous and Tertiary marine and sedimentary deposits underlying and surrounding basins such as San Joaquin Valley, and those found in western states are enriched in selenium. Presser (1994) identified seleniferous deposits in the Coast Ranges of California and the Central Valley with concentrations of selenium reaching 45 mg/kg and median values exceeding 6.5 mg/kg.

Enrichment of selenium in soils and groundwater commonly occurs in arid and semi-arid irrigated areas where application of irrigation water accelerates weathering processes and mobilizes naturally elevated levels of selenium in the soil profile. To reduce effects of salinization of agricultural lands in these areas, such as the southern Central Valley, large volumes of water are used to flush the excess salt and selenium that accumulates in the root zone (Seiler *et al*. 2003). Drainage of excess irrigation water through the system of drains and canals is then necessary to prevent waterlogging of the soils. These drains, however, provide a conduit to carry seleniferous groundwater to surface water bodies and wildlife areas as it was well documented in the case of disposal of agricultural drainage water into the Kesterson Wildlife Refuge. This agricultural drainwater is eventually conveyed to the San Joaquin River, which delivers large selenium loads into the Delta and North Bay. Reported selenium concentrations detected in irrigation drainage are very high and vary between 75 and 1400 µg/L (Amweg *et al.* 2003). The arid climate amplifies evaporation-related enrichment that takes place in lakes and wetlands resulting in selenium concentrations potentially reaching toxic levels.

3.3 Ambient Selenium Levels in the North Bay

Concentrations of selenium in the North Bay water column and bottom sediments have been monitored since the 1980s. Early on, the monitoring effort focused on the northern segments of the Bay because sub-surface drainage of agricultural areas in the San Joaquin Valley and waste streams from oil refineries in the Suisun Bay and Carquinez Strait conveyed large amounts of selenium to the Bay. Regional Monitoring Program (RMP) data, studies by Dr. Greg Cutter's research group at Old Dominion University[2] (Cutter and Cutter 2004, Doblin *et al.* 2006) and the Selenium Characterization Study (Tetra Tech 2012) provide a comprehensive view of selenium conditions in the North Bay. General sampling locations are shown in Figure 2.

The ambient total selenium levels in the North Bay measured between 1993 and 2005 were consistently low and did not exceed 0.5 µg/L (Tetra Tech 2008a). The mean dissolved and total selenium concentrations at each monitoring location ranged from 0.12 to 0.18 µg/L and 0.13 to 0.24 µg/L respectively. Dissolved selenium is the predominant form present in the water column. Particulate selenium, calculated as a difference between total and dissolved

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

selenium, accounts for approximately 10 percent of the total selenium. The data collected during 1999-2005, i.e., following the improved wastewater control measures implemented by the oil refineries in 1999, indicate a slight decrease in concentrations of dissolved and total selenium at 0.10 µg/L (n = 105) and 0.13 µg/L (n = 100). In comparison, mean dissolved and total selenium concentrations for the period of 1993-1999 at the same monitoring locations were 0.17 µg/L (n = 258) and 0.20 µg/L (n = 230). These trends persist through the 2005-2010 period with RMP data showing average dissolved and total selenium concentrations at 0.10 µg/L (n=84) and 0.11 µg/L (n=83).

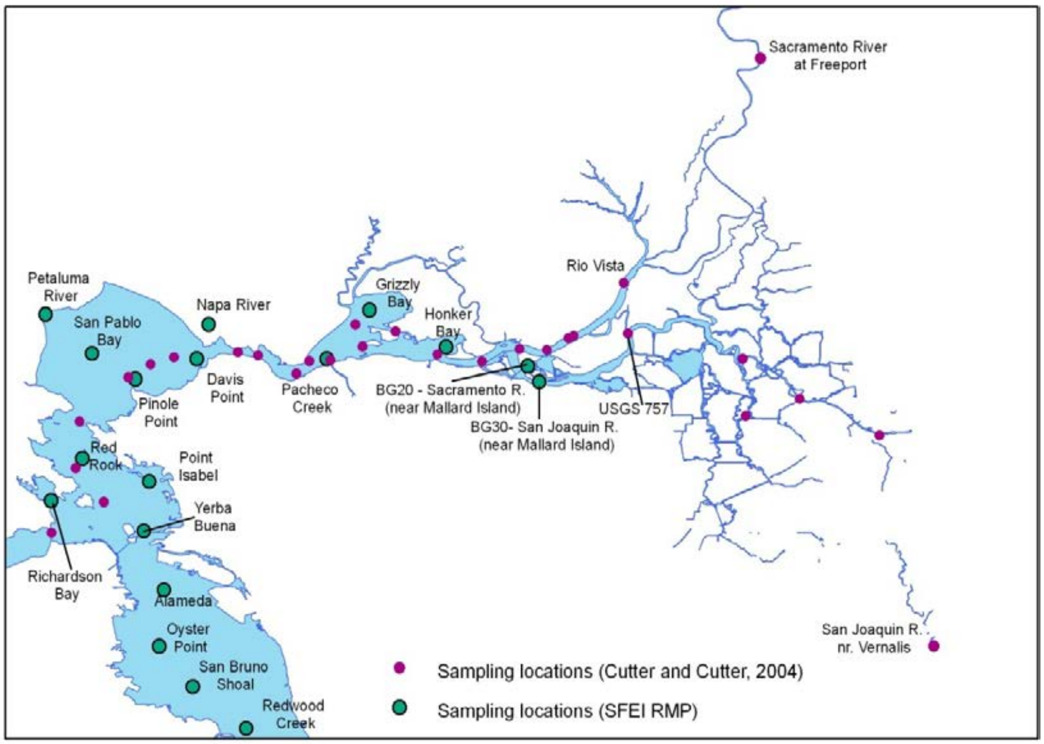


Figure 2: Locations of RMP long-term monitoring sites and sites sampled in 1999

Spatially, total selenium concentrations measured by RMP are marginally higher in the mid-estuarine regions of San Pablo Bay (0.07 – 0.23 µg/L, mean=0.13 µg/L) and Suisun Bay (0.08 – 0.15 µg/L, mean=0.12 µg/L) when compared to the freshwater and marine portions of the estuary (Figure 3). Total selenium concentrations in the western portion of the North Bay are lower, most likely due to ocean exchange and dilution.

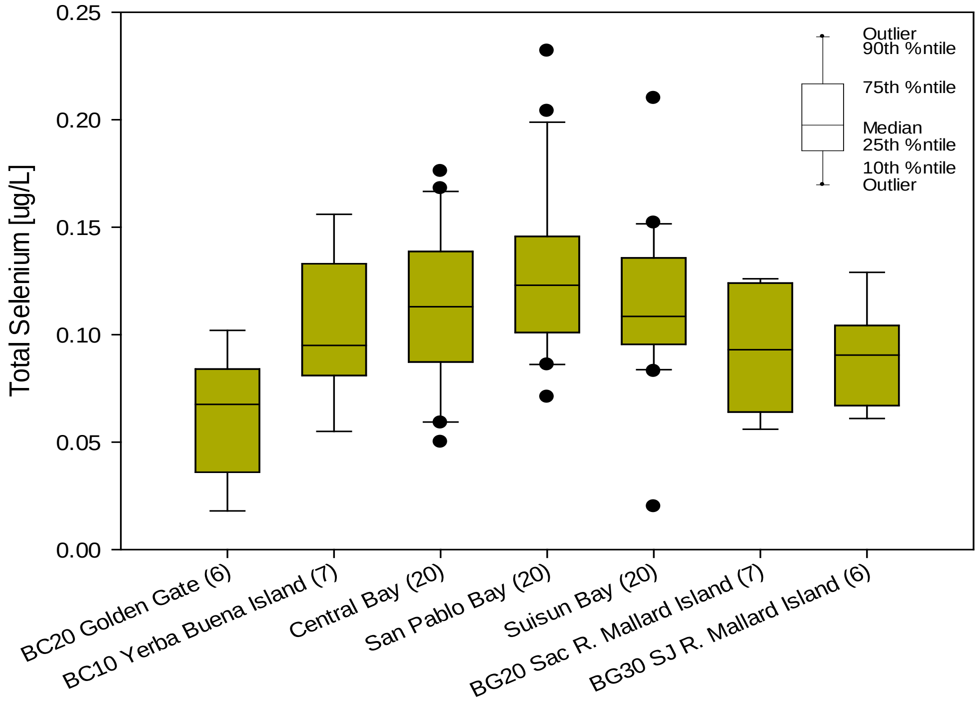


Figure 3: Total selenium concentrations at RMP monitoring sites for the period of 2005-10

Values in parentheses are numbers of samples *(Data: RMP)*.

Figure 4 shows selenium speciation in Suisun Bay and at the downstream freshwater reaches of the Sacramento and San Joaquin Rivers. The composition of selenium species in the North Bay is somewhat different to that observed in the rivers. In the Bay water column selenate is the dominant form and averages above 50 percent of total selenium. However, a relatively high proportion of selenide and selenite is still present, accounting for approximately 20 to 30 percent. In the freshwater flows from Sacramento and San Joaquin Rivers selenate concentrations account for more than 70 percent of selenium with the remainder equally distributed between selenide and selenite. Overall, the speciation in the Bay changes with year and season but it remains within the speciation range found in the rivers.

The changes in selenium composition resulting from the improvements in the wastewater treatment at the refineries are clearly visible during low flow conditions surveyed between 1986 and 2010. In 1986, the more bioavailable selenite fraction of total selenium exceeded 35 percent and almost matched selenate. Since then, the selenite concentration decreased significantly and it now accounts for approximately 15 percent of total dissolved selenium during low flow (e.g. see Figure 4 low flow 1999, 2010).

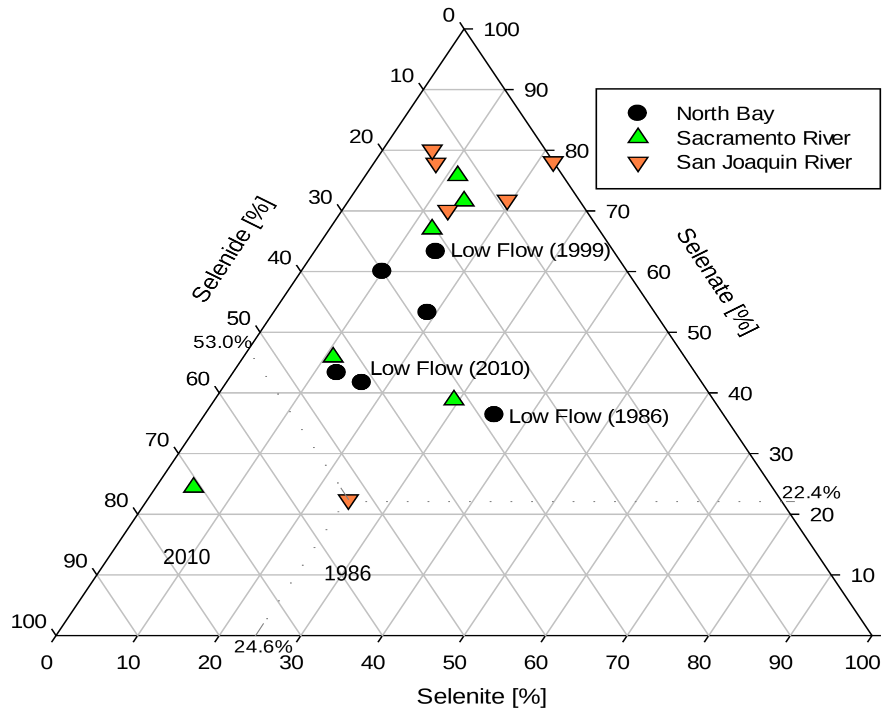


Figure 4: Speciation of dissolved selenium in North Bay and main tributaries

(Data: Cutter and Cutter 2004, Tetra Tech 2012)

In the long term, temporal variations in dissolved and total selenium concentrations are relatively small, and despite inter-annual and seasonal variability, selenium levels in the North Bay remain low (mean = 0.11 µg/L). Dissolved selenium dominates in the North Bay, and the temporal patterns in dissolved selenium closely resemble those in total selenium. The full range of selenium concentrations measured in 2010-12 transects was 0.06 – 0.13 µg/L. The transect sampling has confirmed the notable decrease in dissolved selenium in the mid-estuarine region of the North Bay since 1999 (Figure 5). Higher selenium concentrations are measured in the transition zone between the Bay and the Delta during wet seasons due to an increase in flow from San Joaquin River, while concentrations decline slightly near Golden Gate due to ocean exchange and dilution.

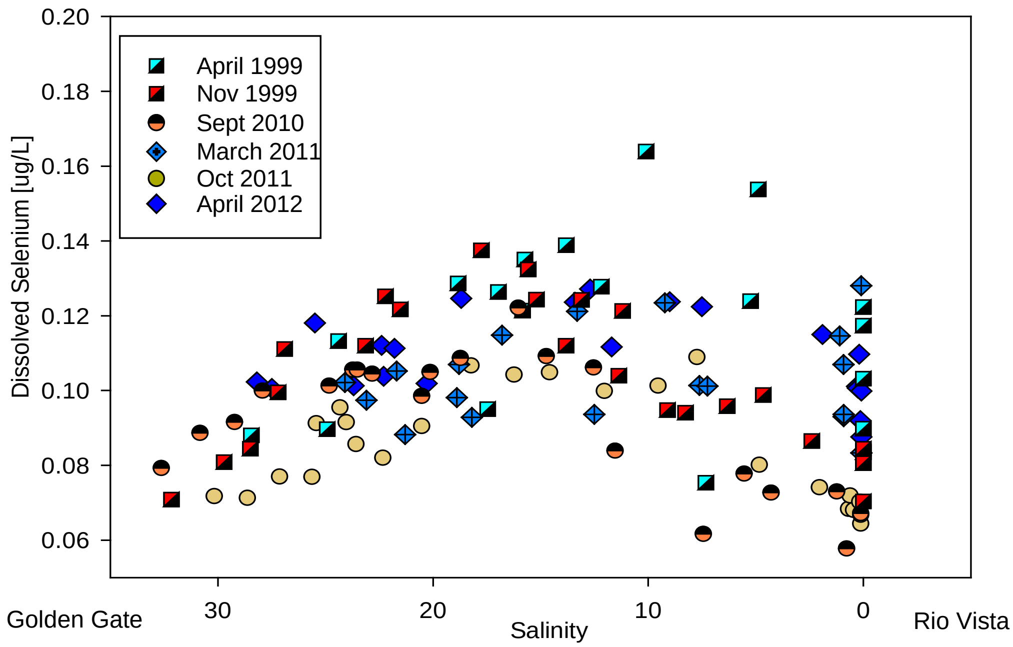


Figure 5: Distribution of dissolved selenium along the salinity gradient for different flow conditions

(Data: Cutter and Cutter 2004, Tetra Tech 2012)

Although most selenium in the water column at any given time is in one of the dissolved forms, the particulate selenium comprises somewhere between less than 1 to 20 percent (mean = 10.3 percent) of total selenium. This particulate selenium is also more readily taken up by bivalves and zooplankton and becomes available for bioaccumulation in higher trophic level organisms. Suspended materials in the North Bay waters include mineral particles, particulate organic matter (non-living) and living organic matters, primarily algae and bacteria. The vast majority of suspended particles originates from various non-point sources discharging to the Bay, may be generated in situ, or may be eroding from the sediment bed, and a small proportion of particulate selenium originates from point sources discharging to the Bay. Studies indicate that particulate selenium is a function of phytoplankton productivity and riverine inputs of sediment to the Bay (Abu-Saba and Ogle 2005). In general, particulate elemental selenium is associated with bed sediments while particulate organic selenium is associated with algal/bacterial uptake, and selenite and selenate are sorbed to mineral particles and/or particulate organic matter.

Particulate selenium concentrations and speciation were measured in 1997-1999 (reported by Doblin *et al*. 2006) and in 2010-2012 (Tetra Tech 2012) using comparable field and analytical methods. Concentrations of selenium associated with particulate material typically range from 0.2 to 1 µg/g[3] with a few exceptions (Figure 6) and do not show trends with salinity, flow or season. The 1999 data and, to a limited extent, the 2010 data (for both wet and dry seasons) suggest an east to west trend, with higher values of particulate selenium at higher salinities. The 2010 dry season and 2011 wet season data suggest an opposite trend, i.e., a decrease toward Golden Gate. These changes may be related to the abundance of total suspended material and the variation of its mineral and organic constituents, which can be affected by short duration events such as riverine flows and the presence of algal blooms. Similar to the dissolved selenium, particulate selenium concentrations measured during 2010-2012 are generally lower (<0.5 µg/g) compared to those measured in 1999 (>0.6 µg/g), and the difference is statistically significant.

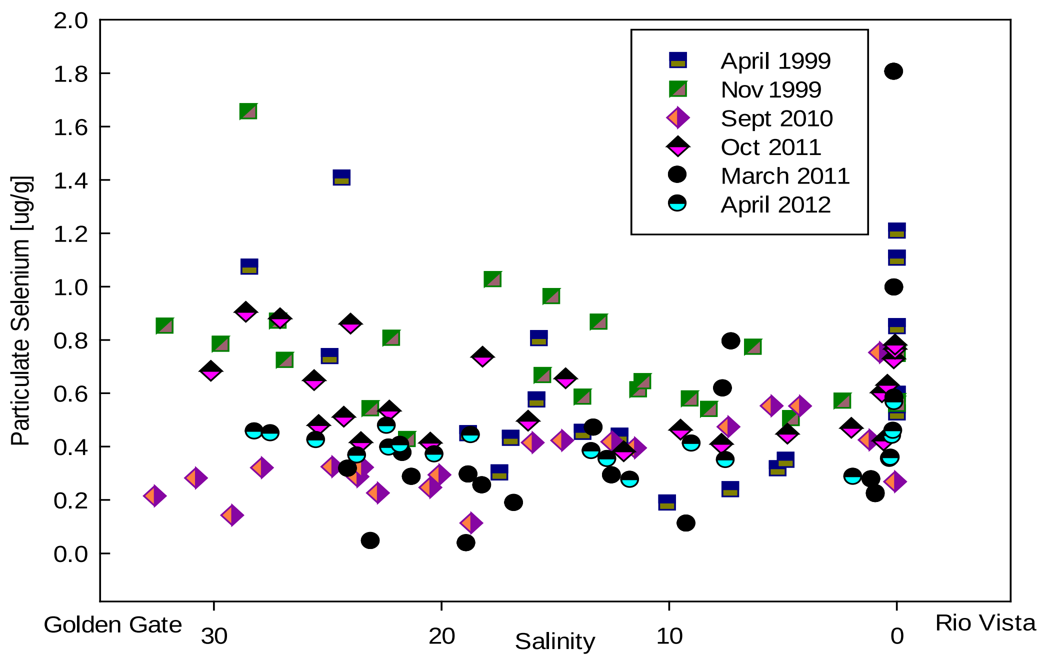


Figure 6: Distribution of particulate selenium along the salinity gradient for different flow conditions

(Data: Cutter and Cutter 2004, Tetra Tech 2012)

The water column inventory of particulate selenium expressed as (total particulate selenium/sum of total particulate and dissolved selenium)*100 has not changed since 1999. The seasonal inventory estimated for current data ranges from 5.3 to 12 percent and

[3] Particulate selenium concentrations are expressed here as µg/g to account for the presence of total suspended material (TSM) in the water column as the quantity of selenium available for filter feeding organisms depends on the amount of TSM.

corresponds to the inventories in April and November 1999, of 11.9 percent and 11.3 percent, respectively (Doblin *et al.* 2006).

3.4 Existing Water Column Objectives

To ensure protection of aquatic life, numeric water quality criteria for toxic pollutants such as selenium have been established by the USEPA in the California Toxics Rule (CTR) and National Toxic Rule (NTR).The aquatic life criteria include one-hour average (acute) and four-day average (chronic) concentrations of these pollutants to which aquatic life can be exposed without harmful effect. Although in 2000, the USEPA promulgated selenium criteria for aquatic life in the CTR for California, these criteria do not apply to San Francisco Bay and the Delta. The Joint Biological Opinion issued by the National Marine Fisheries Service and the Fish and Wildlife Service questioned the proposed criteria for selenium as potentially underprotective of certain threatened and endangered species in California (Federal Register 2000). In order to ensure the continued protection of Federally-listed species the USEPA agreed to reevaluate and revise selenium criteria to include protection of aquatic-dependent wildlife.

In 1992, prior to the CTR, USEPA promulgated selenium criteria for the San Francisco Bay and Delta in the NTR. The water quality objectives that apply in the North Bay are 5 and 20 µg/L (Table 3), and are based on aquatic life guidance criteria for freshwater. The USEPA found substantial scientific evidence that high selenium bioaccumulation was taking place in San Francisco Bay and, under these conditions, concluded that the saltwater guidance criteria did not account for the food chain effects observed in San Francisco Bay. All water column concentrations in the North Bay do not exceed the NTR chronic freshwater criterion of 5 µg/L.

Table 3: Water quality criteria for selenium in Bays and Estuaries

Water Quality Criteria	Chronic µg/L (4-day average)	Acute µg/L (1-hr average)
San Francisco Bay and Delta [1]	**5** (freshwater) [3]	**20** (freshwater) [3]
Rest of California [2]	5 (freshwater) [3]/ 71 (saltwater) [4]	Reserved (freshwater) / 290 (saltwater) [4]

[1] National Toxic Rule Criteria promulgated by USEPA in 1992

[2] California Toxic Rule Criteria promulgated by USEPA in 2000

[3] Expressed as total recoverable selenium

[4] Expressed as dissolved selenium

Even though the water quality objectives in the North Bay are lower than saltwater standards, it has been recognized that they may not be fully protective of the most sensitive species. The USEPA acknowledges that the existing NTR criteria do not fully account for selenium bioaccumulation and have not been derived to protect wildlife and fish.

Draft selenium criteria proposed by the USEPA (2004) for protection of aquatic life recommended a tissue-based criterion as it more directly represents the main pathway for selenium toxicity, which is diet. The USEPA's Action Plan for Water Quality Challenges in the San Francisco Bay/Sacramento-San Joaquin Estuary identifies selenium as one of the seven priority items for action. The plan indicates that the site-specific numeric selenium criteria for protection of aquatic and terrestrial species are under development and they will be expressed primarily as tissue concentrations with water column concentrations forming an additional criteria element.

3.5 Human Health Criteria

Although the North Bay was originally listed as impaired because a health advisory was issued against consumption of diving ducks based on the high selenium content in the waterfowl, the concentrations of selenium found in organisms in the Bay do not pose a risk to human health.

In 2008 Office of Environmental Health Hazard Assessment (OEHHA) developed a new methodology designed to estimate contaminant levels that pose no significant health risk to individuals consuming sport fish and could be used to establish fish tissue-based criteria for fish consumption advisories or pollution mitigation goals. These fish contaminant goals (FCG) are estimated using a standard consumption rate of eight ounces per week (32 g/day) and take into account contaminant nutritional requirements. They are similar in nature to the risk-based consumption limits recommended by the USEPA (2000). The desired contaminant concentration for a nutrient with a non-carcinogenic effect, such as selenium, is calculated as follows:

FCG = [(RfD x BW) – BDL]/CR where:

RfD – chemical specific reference dose (5×10^{-3} mg/kg-day)
BW – body weight of consumer in kg (70 kg default)
BDL – background dietary level in mg/day (0.114 mg/day)
CR – consumption rate as a daily amount of fish consumed in kg/day (0.032 kg/day)

The background dietary level was determined based on studies of nutritional requirements and the results of the National Health and Nutrition Examination Survey. The recommended dietary allowance (RDA) for selenium for general adult population is 55 µg/day and the mean selenium intake from diet only, surveyed among all individuals, is estimated at 113.7 µg/day. For those individuals who supplemented their dietary selenium, the mean intake was found to be 116 µg/day. OEHHA recommends using the value of 114 µg/day as the background dietary consumption rate for computing FCGs for selenium. Using the above equation and assuming a consumption rate of one serving (8 ounces per week of uncooked fish or 32 g/day), which is also the rate used to begin issuing fish consumption advisories, the selenium FCG is 7.4 mg/kg–ww (or 7.4 µg/g). All known concentrations of selenium in fish in San Francisco Bay are well below 7 µg/g–ww[4] and therefore do not pose a risk to human consumers (Figure 7). The numeric targets proposed in Chapter 4 and expressed as dry-weight fish-tissue concentrations are also protective of human health and, therefore, no specific human health target is necessary.

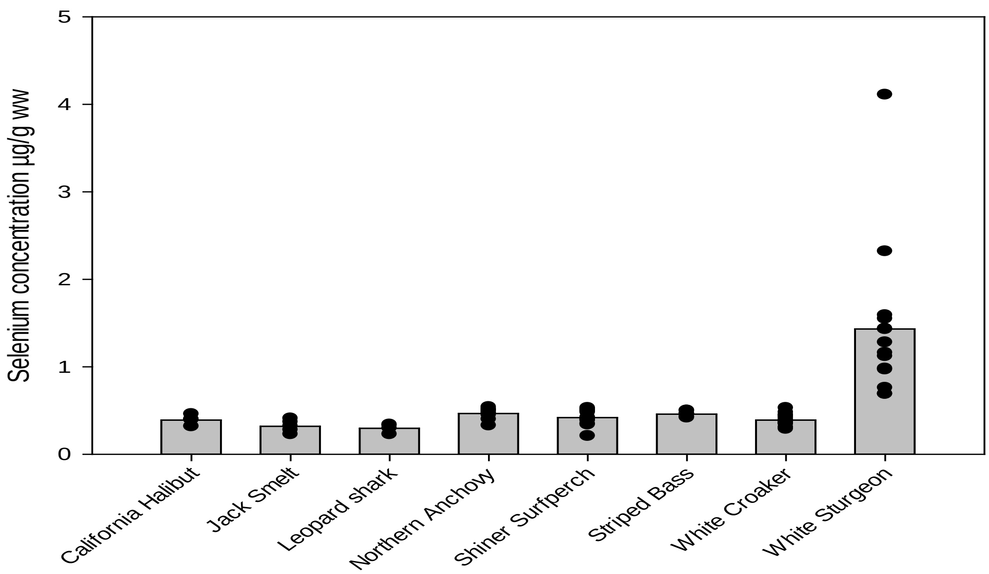


Figure 7: Selenium concentrations in sport fish species in San Francisco Bay in 2009

Bars indicate average concentrations. Points represent individual samples (either composites or individual fish) *(Data: Davis et al. 2011)*

The origin of the 303(d) listing of San Francisco Bay dates back to 1987, when the California Department of Health Services issued a human health advisory against consumption of two species of ducks (Greater scaups and Surf scoters) from the Bay Delta area. Originally the

[4] Assuming an average 75 percent fish moisture content, the FCG of 7.4 µg/g ww equals to 29.6 µg/g-dw.

advisories were issued because of their high selenium concentrations that could potentially impact human health. However, when the 2008 OEHAA approach is used to estimate FCGs for ducks, the concentrations measured in the tissue of surf scoter and scaup (1.34 to 6.4 mg/kg–ww) are all below the estimated FCG human health impact. Therefore, we conclude that selenium human health risk from duck consumption is low.

3.6 Selenium Bioaccumulation and Impact on Aquatic Life

Selenium is a bioaccumulative contaminant, which has a potential to threaten fish and birds due to a dietary transfer. Evidence of fish and wildlife contamination leading to reduced survival and deformities due to selenium in aquatic and terrestrial food webs has been documented extensively (Fan *et al*. 2002, Hamilton 2004, Skorupa 1998). These studies confirmed that once selenium enters the aquatic environment it has a high potential to bioaccumulate in zooplankton and benthic invertebrates, and, to some extent, biomagnify as it reaches top level predators such as fish, birds and mammals.

Bioaccumulation describes the tendency for selenium to be taken up from the environment and stored at increased concentrations by organisms. The rate of bioaccumulation is often site-specific and highly dependent on the forms of selenium present, the environmental conditions, and the life stage and type of organisms. In San Francisco Bay, selenium uptake and bioaccumulation effects are particularly evident in the dominant estuarine clam *Corbula amurensis* (Linville *et al*. 2002, Schlekat *et al*. 2004). The studies found that this clam displayed a 10-fold slower rate for selenium loss compared to common crustaceans, such as copepods and mysids, leading to increased bioaccumulation of selenium. The monthly selenium concentrations monitored in *C. amurensis* found in the North Bay from 1995 through 2010 varied seasonally from a low of 2 to a high of 22 µg/g dry weight (dw) (Kleckner *et al.* 2010). These concentrations are within the range of values that are linked to developmental toxicity in wildfowl and teratogenic effects observed in fish (Schlekat *et al.* 2004). In addition, stable isotope analyses used by Stewart *at al*. (2004) revealed that bottom-feeding fish (e.g. white sturgeon and splittail) exhibited isotope signatures indicative of diets that included bivalves and therefore could be at greater risk from selenium.

Biomagnification occurs where there is a progressive buildup of selenium in organisms at higher trophic levels. Figure 8 depicts conceptually how selenium biomagnifies in the tissues of organisms present in San Francisco Bay. Lemly (1997) reported that biomagnification might lead to a two- to six-fold increase in selenium concentrations between primary producers and forage fish. This, in turn, may have adverse effects on fish and waterfowl even when selenium in the water column does not exceed the water quality objectives.

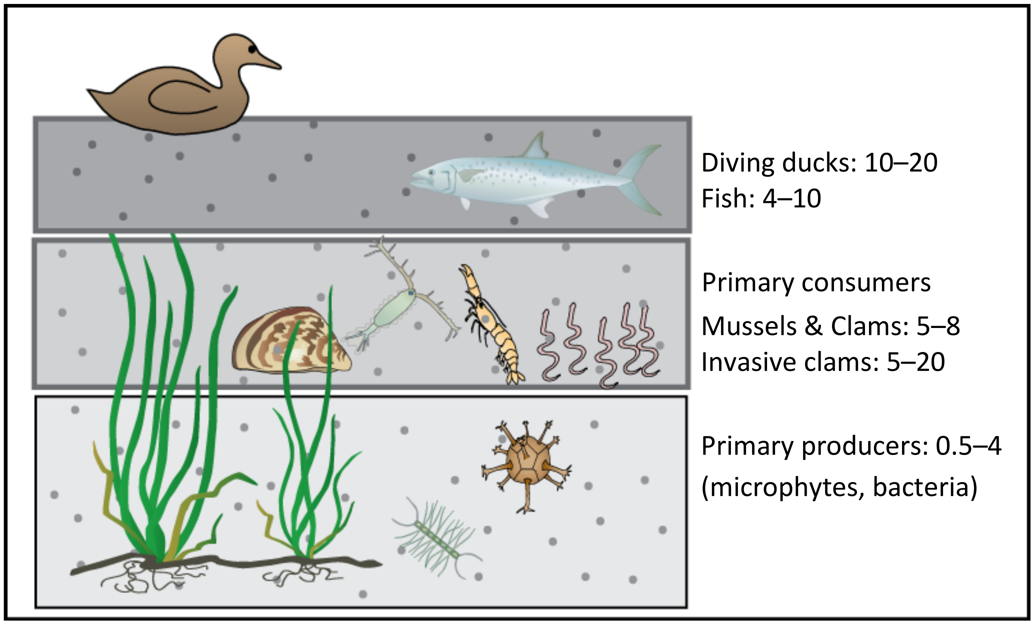


Figure 8: Conceptual representation of selenium biomagnification in North Bay

(Concentrations illustrate the range of selenium found in the North Bay species in µg/g dry weight)

3.7 Toxicity and Selenium Related Risks for Fish and Birds

Our assessment of selenium impairment and a review of toxicological effects has demonstrated that selenium bioaccumulation in the North Bay is only prominent in benthic-based food webs. Among the benthic-based food webs, the clam-eating bottom feeders, such as white sturgeon or Sacramento splittail, are most at risk, with white and green sturgeon being the most susceptible. Although selenium concentrations in white sturgeon remain higher than in any other fish, they are generally below the proposed TMDL target.

In this section we present an overview of the selenium toxicity relevant to fish and birds in the North Bay, describe evidence to suggest that only sturgeon could be affected by selenium, and review concentrations associated with toxic effects to provide a scientific context for establishing the targets for the TMDL in Section 4.

Aquatic and terrestrial organisms are highly sensitive to selenium contamination. They require 0.5 µg/g-dw of selenium in their diet to sustain metabolic processes; however, concentrations that are only an order of magnitude greater than the required level have been shown to be toxic to fish (USEPA 2004). The main toxicological effects in fish and aquatic birds involve reproductive abnormalities, teratogenic deformities, selective bioaccumulation and growth retardation (Eisler 1985).

Toxicity of selenium to wildlife has been researched for many years and numerous studies have documented that, in contrast to many other microelements, chronic toxicity resulting from dietary and food chain exposure causes a much greater problem than toxicity associated with water exposure (for example see: Lemly 1997, Canton and Van Derveer 1997, Hamilton 2002). Reproductive effects in fish and aquatic birds have been identified as the most sensitive biological indicators of aquatic ecosystem-level impacts of selenium.

The discussion of selenium toxicity takes into account the studies and methods described in Tetra Tech (2008b), and refers to the review of the existing selenium dietary exposure benchmarks by Beckon and Maurer (2008). The toxicity-based screening values have been derived from the available scientific literature, which considered either dietary or dietary and waterborne selenium exposures as recommended by the USEPA (2014).

Initial Screening of Available Toxicity Studies

Eighty fish toxicity studies reported from 1987 to 2007 were identified and evaluated using a set of predefined exclusion and acceptability criteria (Tetra Tech 2008b). The reported effects from each study that met the initial criteria were grouped into one of two categories: major and minor effects. Major effects are those that have the potential to impact fish or birds at the organism and/or population level (e.g., increased mortality, reduced fecundity, reduced growth). The lowest observed adverse effect levels (LOAELs), effect thresholds[5], species mean chronic values (SMCV), effect concentrations (EC01 or EC10) and species sensitivity distributions (e.g. Hamilton 2003, 2004) were then used to identify screening levels applicable to fish and birds in the North Bay.

After applying the screening criteria, 19 studies with usable toxicity data were identified as suitable for derivation and comparison of the screening levels for fish, and 23 studies for birds. The studies reported toxic effects associated with dietary or dietary and waterborne exposure for six species of fish: bluegill, fathead minnow, rainbow trout, Chinook salmon, Sacramento splittail and white sturgeon. All experiments, with the exception of one involving Chinook salmon, were conducted in freshwater.

[5] Effect thresholds are calculated as a geometric mean of the no observed adverse effect level (NOAEL) and LOAEL

The available selenium toxicity data showed a broad range of sensitivity among tested fish and included observed threshold effects at very low concentration levels suggesting that the dataset provides a good approximation of the expected effects applicable to most fish species (Figure 9). The larvae of rainbow trout exhibited the highest sensitivity to selenium toxicity with the whole-body LOAEL concentration of 2.3 µg/g-dw for the growth endpoints. The lowest species mean chronic value (SMCV) of 3.0 µg/g-dw was estimated for channel catfish followed by the bluegill and fathead minnow with SMCVs of 5.6 and 6.0 µg/g-dw (Tetra Tech 2008b).

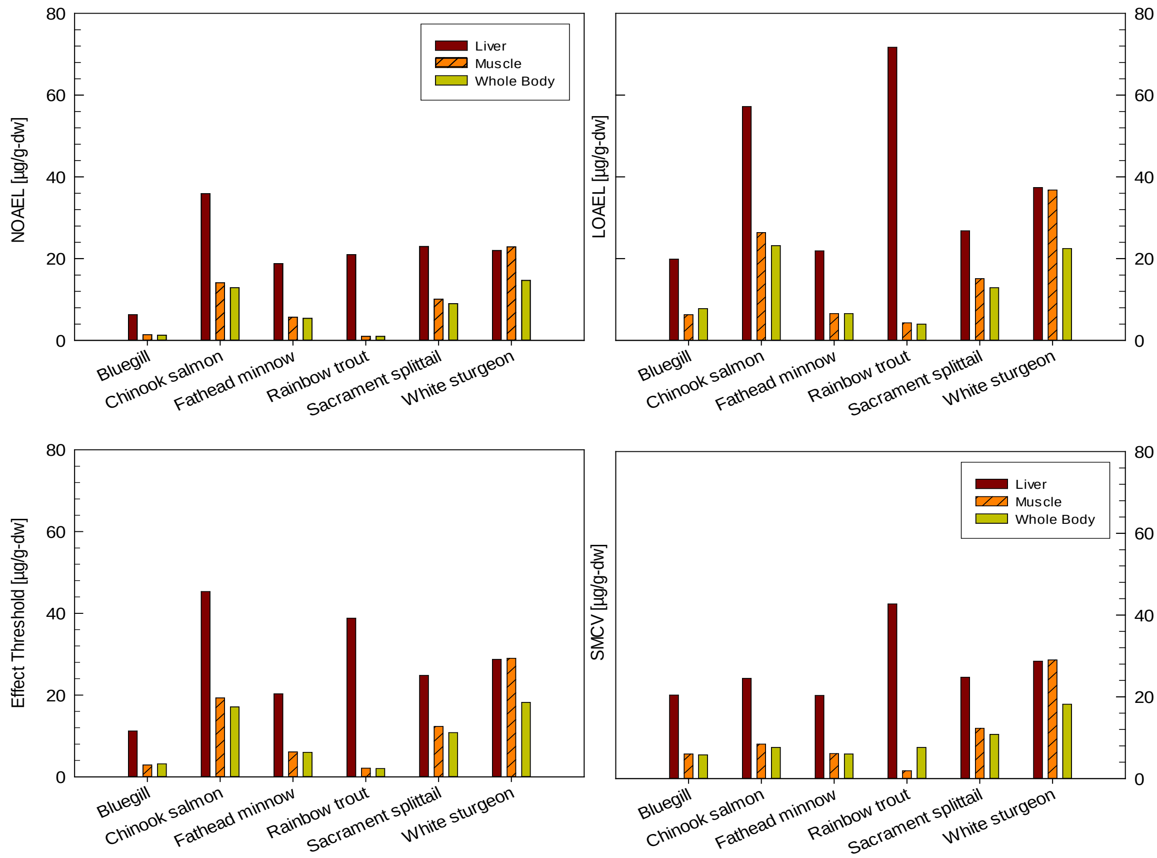


Figure 9: Selenium concentrations in selected fish at which adverse effects may occur

(Figure compiled from the data presented in Table 3-3, Tetra Tech 2008b, showing the most stringent toxicity levels from studies of juvenile fish)

Selenium Toxicity Thresholds for North Bay Fish

North San Francisco Bay does not generally support the most sensitive freshwater fish species year-round, for which the most toxicity data are available. Beckon and Maurer (2008) listed sturgeon, Sacramento splittail and salmon among the fish that could be at risk in the Bay/Delta estuary with white and green sturgeon being most susceptible to selenium exposure. Despite this sensitivity, reproductive and developmental effects in sturgeon are reported at much higher levels than those found in the most sensitive freshwater fish. The whole-body effect thresholds and LOAELs for juvenile Sacramento splittail and white sturgeon are in the range of 6 to 18 µg/g-dw and 12 to 22 µg/g-dw respectively (Figure 9). Toxicity data for green sturgeon are not available. For chinook salmon larvae the lowest whole-body effect threshold and LOAEL measured in freshwater is 7.6 and 10.8 µg/g-dw. An evaluation of white sturgeon, Sacramento splittail and Chinook salmon is provided below to explain their dietary preferences, life histories and evaluated selenium effect levels in relation to the proposed whole body numeric target of 8.1 µg/g-dw.

White sturgeon

Both the white sturgeon and Sacramento splittail feed on benthic organisms including introduced bivalves that have been proven to be very efficient selenium bioaccumulators. This may lead to a greater potential for selenium toxicity for these fish. Native clams and other mollusks were found to dominate the stomach contents of white sturgeon caught by anglers in Suisun Bay (1965-1967) reaching up to 77 percent of stomach volume (see Table 10 in Beckon and Maurer 2008). At the same time, herring eggs dominated stomach content (22.5 to 78.9 percent) in sturgeon caught in San Pablo Bay. The diet of young sturgeon consists primarily of different types of crustaceans, becoming more diverse with age. Larger sturgeons become more piscivorous, and they often feed on fish such as herring and their eggs, starry flounder, American shad and goby (Israel *et al.* 2010). In the recent evaluation of sturgeon samples collected between 1965 and 2013, Zueng and others (2014) found a high proportion of *C. amurensis* in sturgeon diet accounting for as much as 93 percent of total stomach volume. However, they also established that assimilated contribution of these clams to sturgeon biomass was lower than the gut content indicated. This study also showed a relatively large (up to 19 percent) contribution of fish to sturgeon biomass.

The relatively high selenium concentrations (occasionally exceeding 10 µg/g-dw) found in the muscle of white sturgeon collected by the RMP from San Pablo Bay between 1997 and 2009, might be linked to a diet composed of bivalves and in particular *C. amurensis*. Even higher concentrations exceeding 30 µg/g-dw were measured in adult sturgeon caught near Pittsburg in 2000-2001 (USGS data). However, Linares and others (2004) reported selenium in 39 sub-adult sturgeon caught between 2002 and 2004 at levels below 11.9 µg/g-dw with an overall mean concentration of 6.59 ± 0.45 µg/g-dw. This variability is likely a consequence of sturgeon mobility and the fact that their exposure to selenium-laden food items might be intermittent. In addition, there is new evidence to suggest that despite the high proportion in sturgeon's stomach content, *C. amurensis* have low nutritional value and are often excreted without being digested by sturgeon (Kogut 2008, Zeung *et al*. 2014).

Poulton and others (2004) investigated spatial and seasonal patterns of clams and found that densities of *C. amurensis* at six sites in San Pablo Bay declined dramatically over winter (mean= 152 m^{-2}) while other clams were still abundant. The highest density among more than 1700 core samples was only 2206 m^{-2} which is far lower than those commonly found in 1987-88 (>10000 individuals per m^{-2}). An approximately 20-fold decline in the bivalve abundance in San Francisco Bay after 1998 has been also linked to the increased predation by Crangon shrimp, juvenile Dungeness crab and English sole which have persisted at high densities since 1999 (Cloern *et al.* 2007).

Therefore, it may be considered that white sturgeon is not exposed to as much selenium in its diet as previously thought. It is estimated that white sturgeon diet consists of no more than 41 percent of bivalves, which includes *C.amurensis* and other mollusks present in the Bay (Presser and Luoma 2013).

High variability in observed selenium bioaccumulation rates led Tashijan *et al*. (2006) to conclude that juvenile white sturgeon were relatively less sensitive to selenium toxicity than other fish species. In laboratory experiments they showed that even dietary concentrations exceeding 190 µg/g-dw did not affect the survival of sturgeon (the mean survival rate was 99±0.43 percent). This study also determined, on the basis of frequency of kidney lesions, that the adverse effects occurred when white sturgeons were fed 20.5 µg Se/g in the diet. The extensive monitoring of *C.amurensis,* found levels of selenium not exceeding 22 µg/g-dw and averaging at 9.9 µg/g-dw over 2000-2010 period (Kleckner *et al*. 2010). When all sensitive endpoints were considered, no effects were observed with a diet of 9.6 µg Se /g. The corresponding whole-body tissue concentrations with sturgeon fed these diets were 14.7 µg/g-dw (LOAEL) and 11.8 µg/g-dw (NOAEL). The estimated NOAEL is higher than the proposed TMDL target of 8.1 µg/g-dw, which makes the target protective of sturgeon, and includes an implicit margin of safety.

Linville (2006) observed similarly variable selenium concentrations in an experimental study with white sturgeon fed with mostly seleno-methionine diets of 15 to 45 µg/g. In the study white sturgeon was exposed to selenium using two different approaches: (1) by microinjection of L-selenomethionine into larval yolk sacs immediately after hatching and (2) by exposing parent females to dietary selenium (as selenized yeast) for up to six months before they deposited eggs (i.e., maternal transfer exposure). Using regression equations and the data from the Linville's study, USFWS (2012) estimated that incidences of larval developmental defects such as edema and skeletal deformities began to get significant when the EC10 exceeds 15.3 µg/g-dw of selenium in larvae (Figure 10).

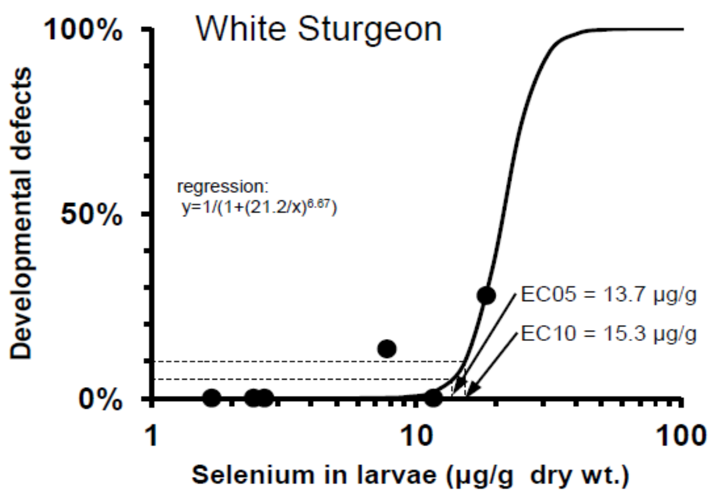


Figure 10: Occurrence of edema and/or skeletal deformities in the larvae from eggs of white sturgeon exposed to dietary selenium.
(*after USFWS 2012; data from Linville 2006*)

Additionally, the concentrations of selenium in larvae, corresponding to 5 percent and 10 percent abnormalities due to maternal transfer, were then translated to selenium concentrations in egg, muscle and whole-body of adult sturgeon (Table 4). We only consider experiments with exposure through maternal transfer as environmentally relevant because it most resembles the way selenium is transferred in the wild. The EC10 effect levels estimated for eggs, muscle and whole-body sturgeon are higher than the values proposed in the 2014 USEPA draft criteria document that forms basis for our TMDL targets.

Compared to white sturgeon, very little direct information is available for the threatened green sturgeon; however, white sturgeon is generally considered to be a representative surrogate species for the green sturgeon (Beckon and Maurer 2008). In one study that tested the green and white sturgeon response to changed environmental conditions, Kaufman *et al*. (2008) concluded that green sturgeon exhibited much greater sensitivity to selenium. The noticeable declines in predator avoidance and reduced swimming performance in green sturgeon were detected at the dietary dose of 20 µg SeMet/g. However, selenium concentrations and dose spacing used in the experiment were too high to be applicable to the conditions in the North Bay and to accurately determine the toxicologically significant thresholds.

Table 4: Selenium effect level concentrations estimated for white sturgeon

Selenium benchmarks in white sturgeon in µg/g-dw [1]								
whole body		muscle		eggs				
EC05	EC10	EC05	EC10	EC05	EC10	Effect	Form of selenium	Exposure
8.51	9.65 [2]	13.1	15.0	14	15.8	larval abnormalities	selenized yeast	maternal diet

[1] *after USFWS 2012; data from Linville 2006*

[2] *Whenever possible, the USEPA used EC10 values in derivation of the draft criteria. The sturgeon-specific EC10 is higher than the proposed numeric target of 8.1 µg/g-dw.*

Furthermore, the protection of green sturgeon using a numeric target based on the white sturgeon data is supported by the habitat and life history of the two species. Green sturgeon is the most anadromous of the sturgeon species and adults and sub-adults spend a large portion of their lives in coastal marine waters outside of the estuary. Typically green sturgeon use the San Francisco Bay during their infrequent (every 3 to 4 years) spawning migrations up to 240 miles upstream the Sacramento River. The tagging and acoustic data confirm that mature green sturgeon do not feed or rear in the Bay but simply continue into natal rivers to spawn (*E. Miller presentation at the Science Symposium, UC Davis, March 3, 2015*). Therefore, the potential for maternal transfer of selenium into developing eggs prior to spawning is low. Green sturgeon juveniles may rear in freshwater and then estuarine waters for 1 to 4 years before dispersing into salt water (Federal Register 2008). However, data for white sturgeon indicate that young fish appear to have low selenium levels in spite of spending prolonged periods of time in the estuary (Linares *et al.* 2004). In contrast to mercury, selenium does not tend to associate with proteins (Presser and Luoma 2013) and there is no evidence of progressive accumulation of selenium with size or age of fish, which could explain the relatively low concentrations in sturgeon compared to concentrations in *C. amurensis*.

Selenium concentrations in sturgeon (muscle) collected in the Bay since 1997, range from 1.8 to 32 µg/g-dw (average: 7.3 µg/g-dw; Figure 11). While samples collected in 2001-2002 are somewhat elevated (3.2 to 32 µg/g-dw; average: 9.7 µg/g-dw), these concentrations are lower than the concentrations measured in 1987-90. Over the last decade selenium levels have been generally below the muscle tissue target of 11.8 µg/g (Figure 11). Most recent comparisons showed that the white sturgeon liver concentrations in 2002-2005 samples were significantly lower than those in the 2001-02 samples (Linares *et al.* 2015). For the entire period of 2000 through 2009 the mean selenium concentration in all 114 samples of sturgeon muscle was 7.5 µg/g-dw. Since 2002 only 5 samples out of 70 have exceeded the numeric target. Despite uncertainties associated with the effect thresholds and the extent of possible selenium impairment, the data demonstrate that selenium concentrations in sturgeon have been decreasing since the late 1990s with the most recent data showing only occasional excursions from the TMDL target. When EC10 sturgeon-specific threshold (15 µg/g-dw, USFWS 2012) is considered, there are only three excursions in the entire data set including the higher concentration period of 2000-2001.

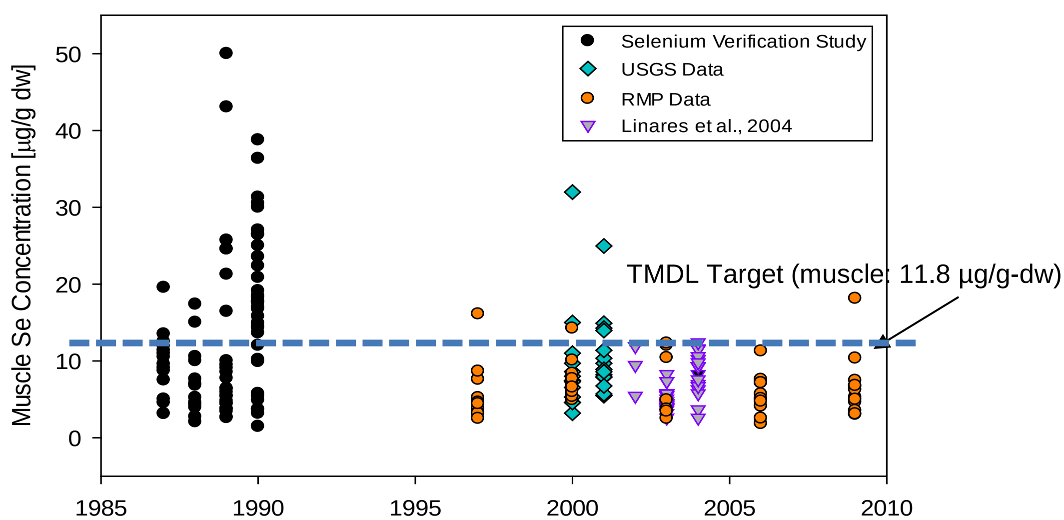


Figure 11: Observed selenium concentrations in white sturgeon in San Francisco Bay

Sacramento splittail

Sacramento splittail could be susceptible to selenium because of their bottom-feeding habits. The diet of splittail collected in Suisun Marsh was dominated by detritus with the proportion of bivalves increasing markedly after the decline of Mysid shrimp in the San Francisco Estuary (Feyrer *et al.* 2003).

Despite bivalves in their diet, splittail tissue collected in 2000 from Suisun Slough (USGS, unpublished data) did not show elevated levels of selenium. In fact, the observed muscle concentrations in juvenile fish varied from 1.5 to 3.5 µg/g-dw and in adult fish from 1.5 to 4.1 µg/g-dw, and were well below known toxicity thresholds. These concentrations are also indicative of background level diets not exceeding 1 µg selenium per gram. Deng and others (2007) observed selenium depletion in the muscle of splittail fed a 12.6 µg/g diet for 9 months that was then followed by 21 weeks of a control diet of 0.4 µg/g. Faster elimination rates were detected at the end of a 21-week depuration in fish previously exposed to high dietary selenium (26.0 and 57.6 µg/g), which might indicate the ability of splittail to cope with the short-term exposure without adverse effects. The authors concluded that based on the observed growth, tissue accumulation and histopathology, splittail that survived the 9-month exposure to 12.6 µg/g or less, could thrive under normal dietary exposure.

One explanation for low tissue concentrations in the North Bay could be related to the fact that splittail prefers fresher parts of the Estuary where *C. amurensis* is not so prevalent, and feeds on many different items; predominantly detritus (50-60 percent) and amphipods, copepods, insect larvae, and bivalves . This fish is known to spawn in inundated terrestrial vegetation in the upper Estuary and their recruitment is strongly associated with the magnitude and duration of floodplain inundation during wet season winter months when the clam population usually experiences a notable decline (Deng *et al.* 2007, Parchaso and Thompson 2002). Feeding studies from Suisun Marsh showed that splittail preferred prey item was *Neomysis* and, in general, they did not switch to alternate or more abundant food items as was observed for other native resident species (Moyle *et al.* 2004). During laboratory experiments Teh and others (2004) determined that at least 9 months of chronic exposure to a diet of 6.6 µg/g was necessary to induce possible deleterious health effects and these conditions are unlikely to occur in the part of the estuary frequented by splittail.

A small number of Sacramento splittail samples (n=12) collected in Suisun Slough in 2000 shows that selenium concentrations in splittail muscle are at the background levels and range from 1.5 to 4.1 µg/g-dw (average: 2.4 µg/g-dw). Life history, intermittent exposure to selenium and dietary preferences strongly suggest that the proposed TMDL targets are protective of Sacramento splittail.

Chinook salmon

Salmonids in the North Bay are potentially among the most sensitive species of fish; however, their migratory nature, the length of time they spend in the estuary and their predominant diet of insects and crustacean imply that these fishes are at lesser risk from selenium than sturgeon, and are not impaired by selenium. Simply put, selenium concentrations in salmon's dietary items found in the North Bay are low, and it is unlikely they will result in excessive bioaccumulation. Because of the inclusion of the toxicity data for anadromous species in derivation of the freshwater criteria the whole-body target is protective of juvenile salmonids.

In contrast with sturgeon and splittail, the diet of Chinook salmon in the estuary consists primarily of insects and crustacean resulting in minimal direct exposure to selenium. A growth and survival study with Chinook salmon conducted by Hamilton and others (1990), also documents that salmonids in the North Bay are not adversely impacted by selenium. The experiments in standardized freshwater and brackish water, during which swim-up larvae were fed one of two different diets, showed survival rate of 94.1 to 95 percent in larvae exposed for 60 days to seleno-methionine diet at concentrations of 9.6 and 5.3 µg/g-dw, respectively. At the higher (95 percent) survival rate, the selenium concentration in tissue of the tested fish was 3.1 µg/g-dw with the mean larval weight just marginally less than the weight of fish with tissue concentration of 0.9 µg/g-dw and selenium diet of 1 µg/g-dw. The residence time of Chinook salmon juveniles in the estuary ranges from a maximum of 64 days (Beckon and Maurer 2008) to less than 40 days (MacFarlane and Norton 2002), which corresponds to the exposure time used in the experiments that did not result in any significant adverse effects.

The calculated whole-body effect thresholds based on the results from the study by Hamilton and others (1990) are 7.6 µg/g-dw for freshwater and 17.1 µg/g-dw for brackish water, and the NOAEL is 5.4 µg/g-dw (freshwater) and 12.6 µg/g-dw (brackish). These calculations exclude the results of the experiments in which larvae were fed field-collected mosquitofish from San Luis Drain, thought to be potentially contaminated by pesticides and heavy metals and, therefore, not representative of the selenium exposure. This is contrary to the findings reported by Beckon (2007), who employed a biphasic model to all the data (including experiments with mosquitofish) from the study by Hamilton *et al*. (1990), and estimated that

20 percent mortality may occur in Chinook salmon with tissue concentration in excess of 2.5 µg/g-dw. The optimum selenium concentration in that interpretation was assumed to be approximately 1 µg/g whole-body-dw. This interpretation has not been confirmed by a toxicity study designed to specifically test these assumptions. In addition, the assumed optimum concentration of 1 µg/g-dw is lower than the natural background concentrations found in fish from areas where selenium is attributed to natural geologic sources (Eisler 1985).

The results of a stochastic population model simulating the chronic level exposure in cutthroat trout, which have similar early life-stage characteristics to those of rainbow trout or Chinook salmon also confirm that the adverse effects from selenium occur at somewhat higher concentrations than calculated by Beckon (2007). Van Kirk and Hill (2007) simulated the conditions in the upper Snake River basin to evaluate sensitivity of the resident cutthroat trout populations to selenium. Based on the modeling results the authors recommended 7 µg/g-dw as the maximum allowable concentration in whole-body fish tissue to protect cutthroat trout. Furthermore, laboratory studies with fish fed with selenium-rich diets demonstrated active excretion of selenium during periods of lower concentrations in the food. The observed excretion was more rapid in fish exposed to higher selenium diets (Hardy *et al*. 2010).

Toxicity Mitigating Conditions

Environmental factors and water quality parameters, e.g., hardness, have been used in the development of aquatic life criteria for toxic pollutants in recognition of their mitigating effects, and to account for the site-specific conditions in a particular water body. Sulfate content and salinity are among the factors that have been shown to potentially alleviate selenium-related toxicity to aquatic organisms. Antagonistic effects from sulfate content on either uptake or acute toxicity of selenate have been reported for algae, aquatic invertebrates, Chinook salmon and fathead minnows (USEPA 2004).

Hansen *et al*. (1993) demonstrated that sulfate concentrations significantly reduced the accumulation of selenium in two aquatic invertebrates: *Chironomus decorus* and *Daphnia magna*. Based on the results of the laboratory experiments, the study concluded that although increased levels of sulfate could not totally prevent selenate absorption, over 40 percent reduction in tissue selenium concentrations was observed in both invertebrates for the selenium to sulfur ratios between 1:0 to 1:480. Similarly, juvenile rainbow trout acclimated in high salinity water (16.8 dS/m) prior to dietary exposure were more resistant to 180 µg/g dietary seleno-methionine treatment and experienced limited mortality (33 percent and 0 percent) compared to tests in freshwater where 100 percent mortality occurred (Schlenk *et al.* 2003). This reduction in selenium uptake has been attributed to salinity and the presence of sulfate ions. It has been demonstrated that competitive interactions between sulfate, selenate, and their metabolic products reduce bioaccumulation of selenium at the bottom of the food web, which, in turn, alleviates selenium toxicity in higher level organisms (see examples in Hansen *et al*. 1993).

Hamilton and Buhl (1990) conducted 24-hr and 96-hr acute toxicity tests with advanced fry of Chinook salmon and coho salmon in fresh and brackish waters simulating the conditions in the San Louis Drain. Although the study focused on examining the impact of multiple contaminants and the sensitivity of various life stages of fish, the reported acute toxicity to selenate and selenite expressed as LC50s were consistently higher in the standardized brackish water compared to tests in freshwater. In addition, the authors estimated the margin of safety from the pooled LC50 data for Chinook salmon, expressed as a difference between selenium levels resulting in no effects and toxic effects. The margin of safety for both selenate and selenite was significantly higher in brackish water with the value for more toxic selenite estimated at 276 in freshwater and 468 in brackish water. Similarly, in a chronic toxicity study with fingerling-sized Chinook salmon exposed to dietary selenium for 120 days, the fish survival was significantly reduced in freshwater but not affected in brackish water (Hamilton *et al.* 1990). In a 10-day seawater challenge test that followed the dietary exposure, the fish survival was significantly reduced but only in fish fed in excess of 35 µg Se/g. Evidence of no effects on growth or survival in fish fed 26 µg Se/g prior to a 3-month seawater challenge was also provided.

Even though the data are limited, fish seem to exhibit much higher resilience to selenium toxicity in saltwater with higher sulfate content, than in freshwater. The results of these studies suggest that ambient levels of sulfate occurring in the North Bay are likely to provide an added level of protection against selenium toxicity and at the same time account for an implicit margin of safety in our review of the screening values for fish.

Evaluation of Selenium Impairment in Birds

Selenium toxicity in birds has been recognized as an issue of concern since the 1980s (Ohlendorf and Fleming 1988, Skorupa 1998). Similarly to fish, selenium bioaccumulation in birds occurs primarily via dietary exposure. While diet could vary significantly and is difficult to quantify in the field, the concentration of selenium in bird eggs provides the most direct and sensitive measure of reproductive impairment. Egg concentrations above 9 µg/g-dw have been associated with reduced hatchability and teratogenesis in mallards (Heinz 1996). In 2009 the USEPA approved the selenium standard of 12.5 µg/g-dw in bird eggs (corresponding to EC10) for the open waters of Great Salt Lake (GSL). In developing the toxicity thresholds for the GSL, the scientific panel considered the sensitivity of multiple aquatic-dependent birds, and endpoints protective of reproductive success and body conditions of the most sensitive species. Selenium concentrations in eggs of double-crested cormorants, Foster's terns and clapper rails found in San Francisco Bay are generally below 6 µg/g-dw and do not exceed the GSL standard. Therefore, we conclude that the birds are not affected by selenium and the bird-specific target is not necessary.

In the section below, we discuss selenium toxicity and concentrations in diet and tissue of bird species that have been identified by Beckon and Maurer (2008) to be the most at risk and are common in the San Francisco Bay/Delta area, and explain why they are not affected by selenium. These species are black scoter, greater and lesser scaup, surf scoter, white-winged scoter and California clapper rail. These birds are considered to be exposed to selenium because of their main feeding habits and/or wintering locations. Although San Francisco Bay is described as an important habitat and wintering area for waterfowl, no direct toxicity information is available for any of the birds species listed above. Instead, this section of the report summarizes the available information on avian toxicity in general and examines toxic concentrations in the diet and eggs of typical laboratory birds, including mallard ducks usually considered among the most sensitive species.

The dietary screening levels reflecting potential adverse effects for bird species in the North Bay were determined based on a review of more than 40 selenium toxicity studies. Chickens and mallards were the bird species for which most information was available. The toxicity data showed a similar broad range of sensitivities and variability as for fish (Figure 12).

The evaluation of toxicity studies confirmed that reproductive success, such as egg hatchability, egg fertility and chick survival was the most sensitive endpoint in the tested birds, especially in mallards. In addition, the results for chickens indicated the growth/survival was also one of the sensitive endpoints. A large variability in the effect threshold ranging from 1.5 to 17.3 may suggest that these birds have potentially greater resilience to selenium toxicity. Similarly, immature mallards seem to be able to tolerate relatively high selenium concentrations reaching 17 µg/g-dw without experiencing adverse effects (Heinz *et al.* 1990).

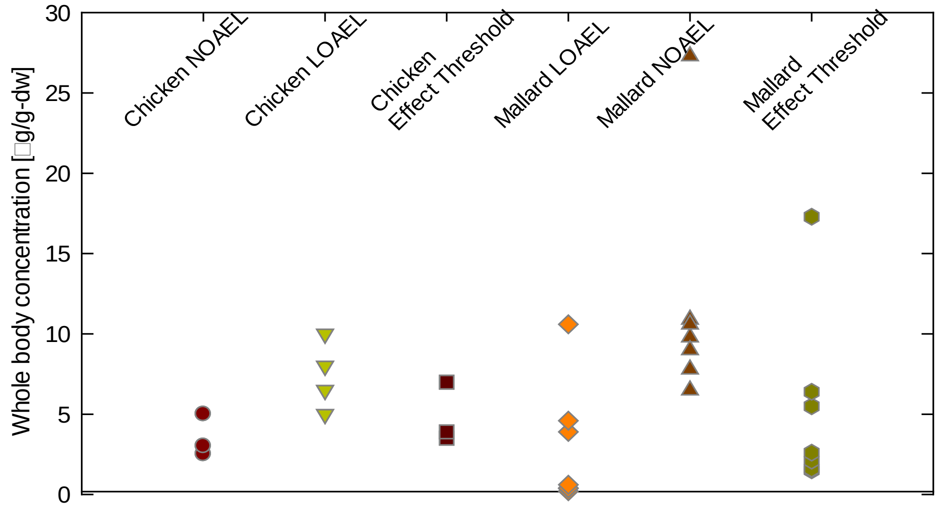


Figure 12: Observed range of dietary selenium at which adverse effects in birds may occur

Since no toxicity data on bird species of concern in the North Bay are available, data from the available bird studies were used and allometric scaling applied to better estimate the pertinent risk levels (Tetra Tech 2008b). In ecological risk assessment, allometric scaling is often used to extrapolate toxic responses observed in avian test species to the wildlife endpoint species of interest (Sample and Arenal 1999). The allometrically adjusted toxicity values account for differences in body weight, metabolism, pharmacokinetics and sensitivity, to allow for the best available estimate of species-specific toxicity when data are lacking. The allometric assessment suggests that most birds of concern in the North Bay share many common characteristics with mallard ducks.

Although selenium concentrations in the diet of birds could be indicative of teratogenicity or reproductive impairment, the most direct way of determining potential toxic effects of selenium in birds is through measuring egg selenium concentrations (Fairbrother *et al*. 1999). In areas without selenium contamination, typical concentrations of selenium in bird eggs are 3 to 4 µg/g, with maximum individual values usually < 5 µg/g (USDOI 1998). However, a review and comparison of the key teratogenicity endpoints for stilts and ducks, indicates that the mean egg selenium EC10 ranges from 12 to 15 µg/g-dw depending on the type of regression analysis used (Adams *et al*. 2003). In 2009 the USEPA approved the selenium standard of 12.5 µg/g-dw in bird eggs for the open waters of Great Salt Lake. All concentrations in Cormorant and Foster's Tern eggs in San Francisco Bay measured from 2002 to 2009 were below 12.5 µg/g-dw (average: 3.95 µg/g-dw, n=46) Figure 13).

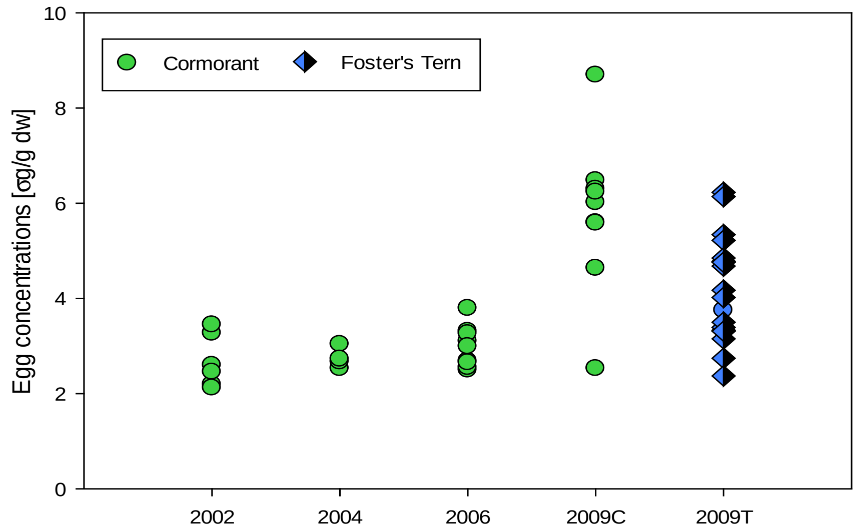


Figure 13: Concentrations of selenium in bird eggs

Clapper rail

Although clapper rail depends on a diet that includes benthic invertebrates, they are littoral feeders that usually do not eat *C. amurensis*, which is mostly subtidal (Presser and Luoma 2013). According to Beckon and Maurer (2008), only a relatively small proportion of clapper rail diet comprises Macoma clams (~7 percent); yellow shore crabs and snails account for less than 5 percent of the diet, and spiders and plant material account for 15 percent each. These birds feed predominantly on plaited horse mussels (>50 percent) and their dietary selenium intake is likely low. The preferred clapper rail diet, together with the fact that their principal habitats include low portions of coastal wetlands and tidal sloughs where the invasive clams are less common, are likely to limit the exposure of clapper rail to dietary selenium.

The results of a study investigating the reproductive success of clapper rail in six Bay Area marshes (including two marshes in the North Bay area: Corte Madera and Wildcat) during four breeding seasons from 1991 through 1999 (Schwarzbach *et al*. 2006) revealed that mean egg tissue selenium concentrations ranged between 1.89 and 2.22 µg/g-dw and were within the background range for avian eggs (1 to 3 µg/g-dw: Skorupa and Ohlendorf 1991), signifying no effect on reproduction. These concentrations are well below the screening level of 8 µg/g-dw that represents the upper end of possible no effect concentrations, Furthermore, the clapper rail egg selenium concentrations declined significantly since the 1980s and were at half of the concentrations found in 1986-87 (mean: 4 µg/g-dw; range 1.6 – 7.4 µg/g-dw). As concentrations in eggs are the most direct way to determine avian embryonic exposure and effects, we conclude that under current conditions the endangered clapper rail are not at risk from selenium exposure.

Surf scoter and Greater/Lesser scaup

Among the North Bay birds, only scoters and scaups are likely to be exposed to selenium concentrations in their diet that may exceed the screening levels, with the greater and lesser scaup and surf scoter being most at risk because of their feeding habits. These diving ducks are common in the North Bay and they feed primarily on benthic mollusks, especially clams and mussels, crustaceans and insects. The results from the 2002 bird study involving tissue and gut content analysis of surf scoters showed that the entire gut content of scoters caught in Suisun Bay comprised the invasive clam *C. amurensis,* while in scoters caught in San Pablo Bay the gut content consisted of 25 percent of *C. amurensis* and 75 percent of the soft shelled clam, *Mya arenaria* (J. Hunt, SFEI, *pers. comm*). Average selenium muscle-tissue concentrations in scoters measured in Suisun Bay and San Pablo Bay were below 4 µg/g-ww indicating a 50 percent reduction compared to the levels observed in 1989, which exceeded 11 µg/g-ww (Figure 14).

The concentrations of selenium in greater scaups in 2002 and 2005, on average, did not exceed 5 µg/g-ww; the levels in San Pablo Bay and Suisun Bay were slightly higher in the most recent samples than in 1986-1987 (average: 2.5 µg/g-ww) . Nevertheless, the results show that typically, for both species, selenium concentrations in 2002-2005 were lower in most regions of the Estuary than in the peak concentration years of the late 1980s.

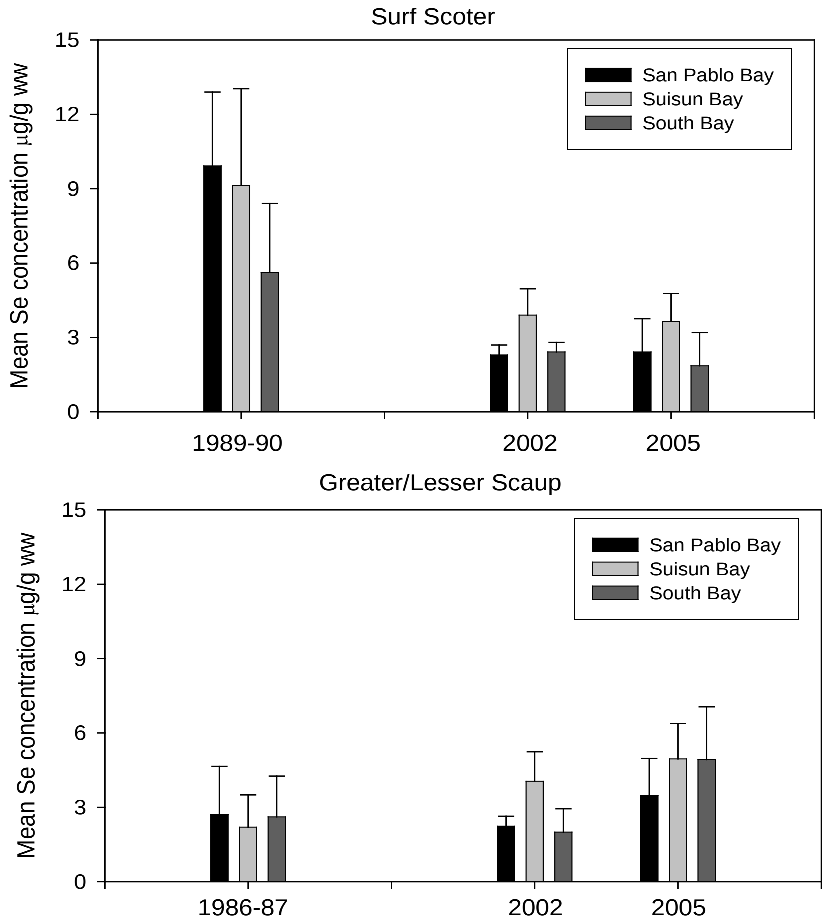


Figure 14: Selenium muscle tissue concentration in diving ducks from San Francisco Bay

(columns represent average concentrations and bars show standard deviation)
Data: DFG 1987, 1988, 1991; SFEI- J. Hunt *pers. comm*. 2002, 2005

A similar reduction in selenium concentrations in aquatic birds from Central Valley has been detected in the Grasslands area, which is affected by selenium, from 1986 to 2005. Paveglio and Kilbride (2007) reported that selenium concentrations in the livers of mallards, pintails, coots and stilts from the North Grasslands declined by 38 percent to 68 percent throughout the 20-year period. For birds collected in the North Grasslands in 2005, the average concentrations of selenium in livers varied from 5 to 8.5 µg/g-dw. The 95 percent confidence intervals (7.1 - 11 µg/g-dw) were highest in black-necked stilts. The authors affirmed that all 95 percent confidence intervals for the 2005 data from the North Grasslands were below the potential reproductive impairment range of 20 to 30 µg/g-dw derived from the US FWS data.

The data from the National Irrigation Water Quality Program have shown that ducks exhibit greater sensitivity to embryonic selenium exposure than other species studied and the response functions developed for ducks represent a generic surrogate for other sensitive birds (Seiler *et al.* 2003). Yet predictions of the teratogenic effects based on the selenium-response functions showed that selenium concentrations of 15 µg/g-dw in eggs would have a minimal adverse impact (~EC01) and the concentrations of 20 µg/g Se dw in duck eggs would cause the incidence of teratogenesis to increase to 5 percent (EC05).

Moreover, studies indicate that both selenium accumulation and depuration rates in birds are rapid. It would take just over 70 days for waterfowl to return to background selenium levels once they leave the selenium rich source, and only within 8 to 10 days selenium concentrations are likely to fall below the known effect thresholds (Heinz *et al.* 1990, Wilson *et al.* 1997). The rapid depuration of selenium by diving ducks during their more than 50-day spring migration from San Francisco Bay to breeding grounds in Alaska and Northern Canada might be responsible for lack of detrimental physiological effects reported and for minimal amounts of selenium deposited in developing eggs. This way the potential for adverse effects in transient and migratory species most at risk from selenium in the North Bay is greatly reduced.

DeVink *et al*. (2008) simulated late spring migration exposure to environmentally relevant doses of dietary selenium in an experimental study with captive scaups. The authors found no treatment effect on body mass, breeding probability, or clutch initiation dates after a 30-day exposure to 15 µg/g and 7.5 µg/g of selenium as selenomethionine, after which excess selenium was removed from the diets prior to laying. Moreover, the results showed that selenium concentrations in eggs decreased rapidly after selenium-supplemented diets were removed and within 12 and 8 days were below the teratogenicity threshold of 9 µg/g-dw. The overall conclusions indicated that these dietary exposures were not sufficient to adversely affect body mass or reproduction in scaup that subsequently migrated to uncontaminated breeding areas.

The selenium diets used in the study reflected the maximum reported concentrations (7.4 µg/g) in zebra mussels from sites along the St. Lawrence River and an environmentally elevated dose (15 µg/g) greater than the maximum reported concentration (11.5 µg/g) in zebra mussels from the Great Lakes. Areas surrounding Lake Erie have recently experienced significant increases in diving duck populations that are attributed to the invasion of the zebra mussel. Selenium concentrations in *C. amurensis* in the North Bay are very similar to those found in zebra mussels and used in the study. The levels in *C. amurensis* measured in 1999 ranged from 7.2 to 16.7 µg/g (mean 11.0 µg/g) and over the last ten years of data the mean was 9.9 µg/g (n=498).

One of the most compelling signs so far that the conditions in the Bay may have lesser than expected impact on diving ducks comes from the analysis of selenium in eggs of scoters. In 2005-2006, twenty-three female scoters from the Bay area were marked with satellite transmitters and their migration was tracked to the breeding areas (De La Cruz, USGS, *pers. comm.*). Eleven fresh eggs were collected from three nests of the marked birds. The concentrations of selenium in these eggs were 1.71 +/- 0.12 µg/g-dw, well below those thought to be of concern for other sensitive bird species and within the normal range of concentrations:1 to 3 µg/g-dw (Skorupa and Ohlendorf 1991).

Although selenium levels in tissue of diving ducks feeding and wintering in the North Bay appear elevated, these ducks do not exhibit decreased body conditions that would affect reproduction or survival. Analysis of lipid and protein reserves, which are essential for survival during prolonged energy deficits such as migration to breeding grounds, indicates that these selenium concentrations had little, if any, impact on ability to store or mobilize energy for maintenance or survival, and do not contribute to increased oxidative stress or impair tissue health (Badzinski *et al.* 2009, Wainwright-De La Cruz 2010). These authors hypothesized that the lack of chronic health effects in ducks and sea birds might be due to the higher tolerance to selenium toxicity, and their life history during which they evolved mechanisms to sequester and metabolize trace elements more efficiently than freshwater birds.

4 NUMERIC TARGETS

Numeric targets identify specific water column, sediment and/or tissue indicators that express the desired conditions of the water body and ensure attainment of the water quality standards including water quality objectives and beneficial uses. TMDL targets are often set to the applicable numeric water quality objectives. However, the existing water quality objectives (Table 3) may not ensure adequate protection of aquatic organisms in the North Bay because they were derived from toxicity studies based on direct water exposure rather than exposure to dietary selenium. Comparison of selenium bioaccumulation via waterborne versus dietary routes shows evidence that water-only toxicity tests may underestimate selenium risk and that selenium biotransformation by algae and zoobenthos adds substantially to the total exposure of higher trophic level organisms. In addition, the National Marine Fisheries Service and the Fish and Wildlife Service considered those objectives as underprotective of certain threatened and endangered species in California.

4.1 Fish Tissue-Based Numeric Targets

The current scientific consensus is that fish tissue concentrations represent chronic adverse effects of selenium better than the conventional water concentration approach. Therefore, we propose the USEPA fish tissue-based draft criteria (2014) as basis for the numeric targets for the TMDL (Table 5). The whole-body and muscle tissue concentrations were derived directly from egg/ovary concentrations and reflect the most sensitive reproductive endpoints in freshwater fish, making them more stringent than the sturgeon-based targets alone (see Table 4).

Table 5: Proposed numeric targets for selenium in the North San Francisco Bay

Fish Tissue Targets [1]	Water Column Target
8.1 µg/g whole-body dry weight	**0.5** µg/L (dissolved total selenium)
11.8 µg/g muscle tissue dry weight	

[1] The draft fish tissue criteria proposed by the USEPA are undergoing a review and may change (USEPA D. Fleck *pers. comm.*). We do not expect the revisions to be substantial enough to affect the proposed water column target and/or the TMDL findings.

While selenium toxicity has been studied predominantly in the freshwater environment and the research has focused on warm water fish, new information is emerging showing that coldwater fish such as in the North Bay are more resistant to adverse impact of selenium (Chapman 2007, Schlenk *et al.* 2003). It has been suggested that since sulfate levels should be higher in brackish and marine waters than in freshwaters, the numeric target based on the predominantly freshwater toxicity studies is more stringent and, subsequently, offers an added level of conservatism to the target value.

The toxicity data used in the derivation of the freshwater criteria are relevant to all fish species found in the North Bay. Thus the proposed targets are protective of benthic clam-eating fish such as sturgeon that are particularly vulnerable to selenium exposure, as well as any other potentially sensitive fish. Consistent with the USEPA recommendations, we also propose a water-column target which represents an equivalent water-column concentration translated from the more conservative fish whole-body target.

Our targets were selected using the latest science, a comprehensive literature review, and the most recent guidance and information following the release for public review of the draft aquatic life criteria for freshwater by the USEPA in May 2014. The USEPA draft criteria document provides suggestions on the laboratory experiments and appropriate effect levels for establishing site-specific objectives, and recommends a methodology for translating the concentration of selenium in fish tissue to the concentration in water. It also recognizes that selenium biochemistry in an aquatic ecosystem is complex and depends on resident species characteristics and site-specific conditions, which makes establishing uniform criteria for all water bodies difficult. Furthermore, experimental data reported in the literature show a variety of toxic effects that may vary significantly from fish to fish and from area to area, and often result in reporting a wide range of concentrations at which impairment may occur. Nevertheless, recent studies concur that selenium-related toxicity in fish results from diet and maternal transfer. The highest levels of selenium in eggs are usually found in fish with the highest tissue concentrations. Most of the significant adverse effects of selenium in fish are associated with reproduction and larval deformities.

Region IX of the USEPA is working on developing site-specific water quality criteria for selenium in San Francisco Bay and California. The anticipated date for release of these criteria is June 2016. This TMDL relies on the USEPA approach to develop targets but does not adopt new water quality objectives.

Attainment of the fish tissue targets for selenium TMDL in the North Bay will be evaluated by measuring concentrations in sturgeon muscle and comparing them against the target of 11.8 µg/g-dw. Sturgeons are long-lived fish found year-round in the Bay with a high propensity to bioaccumulate selenium because of their feeding preferences and reproductive biology. They feed predominantly on benthic organisms including the invasive clam, *Corbula amurensis,* which is very efficient in accumulating and retaining selenium. Sturgeon exposure is further exacerbated by its long reproductive cycle during which selenium is transferred and stored in the developing eggs, forming a stable selenium reservoir in reproductive females. Attainment of the fish tissue target in sturgeon will ensure that all other fish species that reside in San Francisco Bay or migrate through the Bay to spawning locations in freshwater reaches of Sacramento and San Joaquin Rivers are also protected, and provides an implicit margin of safety as these other species will have significantly lower selenium concentrations than sturgeon. In addition, the proposed TMDL fish-tissue targets (Table 5) are more stringent than the effect level concentration (EC10) of 15 µg/g-dw estimated using sturgeon-specific laboratory experiments of maternal transfer of selenium (USFWS 2012).

The Water Board will continue to evaluate attainment of the fish tissue targets and the water column target following the methods currently in use by the Regional Monitoring Program (RMP) to ensure consistency and data comparability. The number of samples collected to determine compliance with the targets will be based on the desired statistical power needed to demonstrate trends and differences over time. We will also evaluate the use of tissue plugs as a surrogate for sampling from a whole fish. If plug sampling is found to be sufficiently accurate, it may become the standard methodology for future sample collection by the RMP and provide an opportunity to monitor sturgeon nonlethally, through collaboration with the California Department of Fish and Wildlife and other agencies.

4.2 Water Column Target

The dietary transfer of selenium from the bottom of the food web to clam-eating fish (sturgeon) and the allowable water column concentration (water column TMDL target = **0.5 µg/L,** Table 5**)** were estimated with the ecosystem-scale selenium model (Presser and Luoma 2010b), the tool used by the USEPA to evaluate selenium transformations in San Francisco Bay, and to derive the water-column criteria for lotic and lentic waters.

Derivation of Allowable Water Column Concentrations

Although aqueous selenium concentrations could not be linked directly to bioaccumulation in fish, transformation from dissolved forms to living organisms takes place at the base of the food web and for that reason it has bearing on the amount of selenium available for higher level predators. Moreover, speciation of dissolved selenium controls transformation reactions between dissolved and particulate forms (e.g. sediments, detrital particles, and primary producers), and the transformation efficiency from dissolved to particulate forms ultimately determines food web concentrations of the element (Presser and Luoma, 2006).

The ecosystem-scale model provides a simplified way to model site-specific food web structures, and translate tissue-based objectives to concentrations in the water column that are easier to measure (Luoma and Presser 2009; Presser and Luoma 2010b, 2013). Figure 15 shows the conceptual components of the model. The equations and model parameters are listed in the Box below.

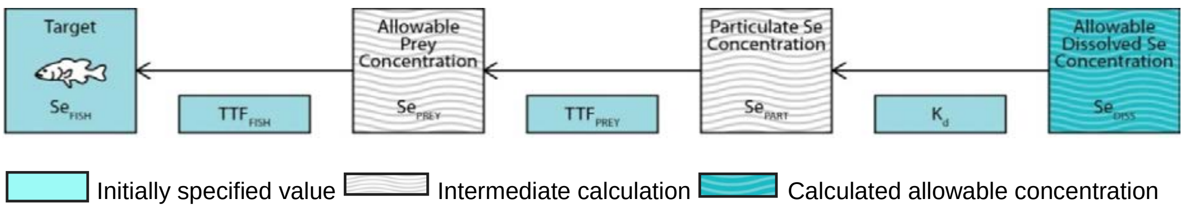


Figure 15: Simplified diagram of components in ecosystem-scale selenium modeling

Box 1

$$\boldsymbol{C_{water}} = \frac{Concentration_{fish}}{\boldsymbol{TTF_{sturgeon}} * \boldsymbol{TTF_{prey}} * \boldsymbol{K_d}}$$

$$TTF_{sturgeon} = \frac{Concentration_{sturgeon}}{Concentration_{prey}}$$

$$TTF_{prey} = \frac{Concentration_{prey}}{Concentration_{particulate}}$$

$$K_d = \frac{Se_{particulate}}{Se_{dissolved}}$$

Where:

C_{water} – modeled allowable dissolved Se concentrations in water column

$Concentration_{fish}$ – TMDL target in µg Se/g-dw in whole-body

$TTF_{sturgeon}$ – trophic transfer factor from diet to fish

TTF_{prey} – trophic transfer factor from particulates to prey items

K_d – partitioning coefficient [L/kg]

Biodynamic trophic transfer factors (*TTFs*), which define species-specific uptake and retention of selenium and environmental partitioning factors (K_d*s*) describing a ratio of particulate to dissolved selenium in the system, are required to quantify the relationships between protective concentrations in fish and dissolved concentrations in water column.

In the absence of rapid growth three biodynamic constants: assimilation efficiency, ingestion rate and efflux rate are combined to calculate *TTFs*. For each species, a *TTF* can be derived from laboratory experiments, literature estimates or from field data. K_d*s* define a ratio between concentration of selenium in particulate material (µg/g) and selenium dissolved in water (µ/L). Among all parameters required in the ecosystem-scale translation, the largest uncertainty is associated with measurement and selection of the K_d values.

After selecting the target fish species and identifying the relevant food-web, selenium concentration in water column protective of the most sensitive species can be evaluated using the ecosystem-scale model. For the North Bay, the more conservative TMDL target expressed as concentration in the fish whole-body and the white sturgeon food web is used to derive the allowable water column concentrations.

While the estimates of the allowable selenium concentrations presented here reflect white sturgeon feeding preferences and physiological factors, the higher potential sensitivity of green sturgeon, albeit with much lower exposure, is also considered by:

- Electing more conservative freshwater fish tissue criteria as the TMDL targets;
- Applying conservative parameter values in modeling; and
- Selecting lower dissolved water column concentrations from the overall range of modeled values.

As a result, the estimated water column target is lower compared to the scenario when the white sturgeon–specific effect level concentration is used (9.65 µg/g-dw wb), and an implicit margin of safety is included in our analysis to ensure protection of potentially more sensitive green sturgeon.

The following sections discuss selection and importance of site-specific input values and conditions necessary to model selenium transport, fate, and exposure of clam eating fish, primarily sturgeon, in the North Bay.

Sturgeon Food Web and Trophic Transfer Factors

The benthic food web from suspended particulate material to *C. amurensis* to sturgeon was chosen to translate the TMDL target to dissolved selenium concentrations in water column. As bivalves accumulate selenium to high levels, this translation is the most environmentally protective of all fish species and beneficial uses in the North Bay. *TTFs* indicate an organism's potential to bioaccumulate selenium from its dietary uptake and provide a link between particulate, invertebrate, and predator selenium concentrations. TTF_{prey} and $TTF_{predator/fish}$ describe a simplified ratio of the selenium concentration in each animal to the selenium concentration in its food.

Sturgeon are opportunistic feeders with diverse diet changing with age. Juveniles may consume a great variety of items such as benthos, insects, pelagic fry and zooplankton, amphipods and shrimp. Larger sturgeon are presumed to become more piscivorous, consuming hearing and their eggs, American shad, starry flounder and goby as well as a large proportion of native and invasive clams and shrimps (Israel *et al.* 2010). For modeling, the sturgeon's diet was assumed to comprise 40 percent of *C. amurensis,* signifying the highest selenium concentrations of all clams found in the North Bay, and 60 percent of annelids and benthic crustaceans (D. Fleck, USEPA, *pers. comm*.). Under the simplifying assumption of the sturgeon's diet consisting of these two general food assemblages ($TTF_{C.\ amurensis}$ = 8) and crustaceans (*TTF* =0.6 – 2, average 1.3) the combined diet *TTF* (TTF_{prey}) is 4.0.

TTF C. amurensis

The calculated kinetic *TTFs* in marine bivalves (clams, oysters and mussels) range from 1.6 to 23 and are among the highest of all aquatic organisms (Supplemental Table B, Supporting Material: Presser and Luoma 2010a). For *C. amurensis* we used the *TTF* estimated with physiological parameters from laboratory experiments as suggested in the USEPA draft criteria document for freshwater. Table 6 shows the experimental data and the kinetic *TTFs* determined for *C. amurensis*. The highest *TTF* of 8 (range 3.6 to 8) was selected for modeling to provide additional margin of safety.

Presser and Luoma (2010b) proposed much higher *TTF* for *C. amurensis* (*TTF*=17). They assumed that clams somewhat preferentially seek organic fraction in the suspended particular material they feed on, and adjusted the values of AE and IR to account for suspended particulate material speciation using available particulate selenium and carbon concentration data. As concentrations and speciation of particulate material is highly dependent on phytoplankton species and phytoplankton abundance, residence time, and other hydrological conditions these estimates are likely to be more uncertain than the laboratory-derived *TTFs*. In addition, it has been noted that at sites with low selenium concentrations (< 1 ug/L) the invertebrate *TTFs* calculated based on field datasets maybe highly variable and caution is advised in interpreting these site-specific values as representative of the entire water body (Presser 2013).

Table 6: Literature-based TTFs for *C. amurensis*

Species	**AE** assimilation efficiency (%)	**IR** ingestion rate (g/g-d)	**k_e** elimination rate (/d)	***TTF*** (AE * IR/k_e)	**Reference**
C. amurensis	0.45-0.80	0.25	0.025	4.5 - **8.0**	Schlekat *et al.* 2002
C. *amurensis*	0.36-0.54	0.25	0.025	3.6 - 5.4	Lee *et al.* 2006

TTF white sturgeon

Although estimated *TTFs* may vary by an order of magnitude, they appear much less variable in fish species than in the invertebrate. In fish selenium does not generally associate with specific proteins, which prevents progressive accumulation with size or age, and the observed level of magnification is significantly reduced compared to, for example, mercury (Presser and Luoma 2013). In addition, there is anecdotal evidence to suggest that sturgeon is able to depurate selenium, which causes the concentrations of selenium in sturgeon tissue to plateau after reaching maturity.

The available *TTFs* for white sturgeon are regression estimates in the range of 0.6 to 1.7 estimated with limited data collected in the 1990s (Stewart *et al.* 2004). Presser and Luoma (2010a, b) compiled all available information and recommended a generic TTF for fish of 1.1. This value represents a mean *TTF* derived from laboratory experiments and from matched field datasets in marine and freshwater environments. *TTFs* derived from biodynamic laboratory experiments range from 0.51 to 1.8. *TTFs* for different fish species derived from field studies are in the same range as the sturgeon *TTFs* (0.6 to 1.7).

For the purpose of modeling the selenium accumulation potential in sturgeon we used the *TTF* of 1.1. Given the fact that sturgeon *TTFs* calculated based on site-specific information are 0.79 in the seaward portion of the North Bay and 0.63 in the landward portion (Table D4 in Presser and Luoma 2010b), and the likely capacity of sturgeon to regulate selenium concentrations in their tissue, the use of the generic *TTF* of 1.1 in modeling is conservative, considers species other than sturgeon that could be sensitive to selenium (e.g. Sacramento splittail) and ensures protectiveness of the simulated water column concentrations.

Partitioning Coefficients (K_ds)

Partitioning of selenium between water and particulate material is a dynamic biogeochemical process. Hence, the distribution coefficient (K_d) which describes the fraction of selenium associated with particulate matter at any given time and location may vary by many orders of magnitude (Presser and Luoma 2009). In fact, K_d varies more widely than any other parameter used in the translation process and careful consideration must be given while selecting the appropriate values. By definition, K_d values greatly depend on selenium speciation in water column, and on the precision and accuracy of measurements of total suspended material that is necessary to determine selenium concentrations on particulate material in µg/g. In addition, in systems such as the North Bay, where dissolved selenium concentrations are very low (full range of concentrations measured in 2010-12 transects was 0.06-0.13 µg/L), the K_d ratios could become artificially inflated because dissolved concentrations in the denominator are very low.

Presser and Luoma (2013) attributed the largest part of variability in observed K_d values to the most landward and seaward samples in the transects. The downstream transport of contaminated particles from San Joaquin River and biological transformations in Central and San Pablo Bays that deplete selenium in water column in favor of enriching the particles might explain this variability.

The ECoS model simulations confirm that despite dissolved selenium concentrations remaining low, the particulate concentrations increase with distance from the Delta resulting in higher values of K_ds (Tetra Tech 2010). These are caused by an increase in the ratio of chlorophyll *a* to total suspended material (TSM) across the North Bay. The simulated mix of particulate selenium across the North Bay, with increasing proportion of organic selenium, is shown in Figure 16.

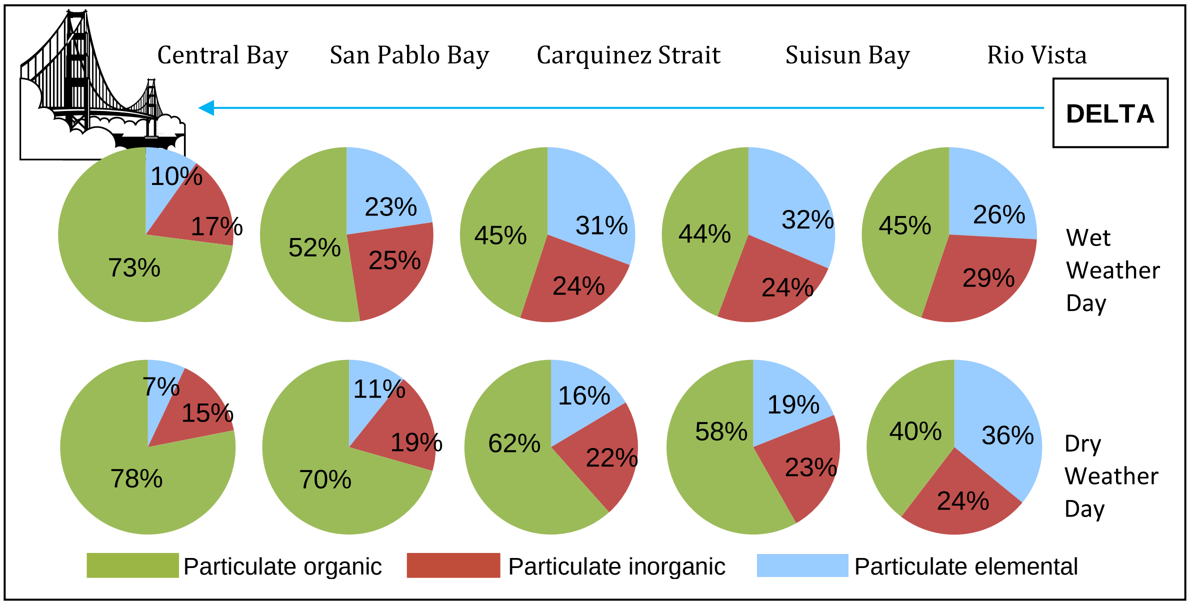


Figure 16: Changing mix of particulate selenium from the Delta to the Golden Gate

The available transect data collected in 1998-99 and more recently in 2010-12 provide spatially and temporally matched data for derivation of K_ds that cover a wide range of flow and residence time conditions. The range of K_ds calculated based on the entire transect data varies from 378 to 26912. These extremely low and high K_ds may not truly represent the linkage between dissolved and particulate concentrations in the Bay system but might be an artifact of very low selenium concentrations in the dissolved phase, which results in overall low accuracy of the measurements. As recommended by Presser and Luoma (2013), in order to avoid artificially high K_ds driving the calculated allowable selenium concentrations below the background levels, the transect data were geographically restricted to the middle zone of salinity range encompassing Suisun Bay and Carquinez Strait (the so called focused seaward transect). This results in narrowing the range of K_ds to 712 to 8845. Figure 17 illustrates focused seaward locations determined for October 2011 transect. K_d statistics for focused seaward segment of the transects from 1999 through 2012 are shown in Figure 18.

Although conceptual models indicate that the prolonged dry periods contribute to formation of more bioavailable forms of selenium (Presser and Luoma 2010b), comparison between the wet and dry seasons does not show that K_ds are statistically different. Therefore, to account for the range of conditions that could influence the trophic transfer of particulate selenium through the benthic food web, the focused seaward portion of the transects from both dry and wet seasons (1998-99 and 2010-12) were used in the modeling.

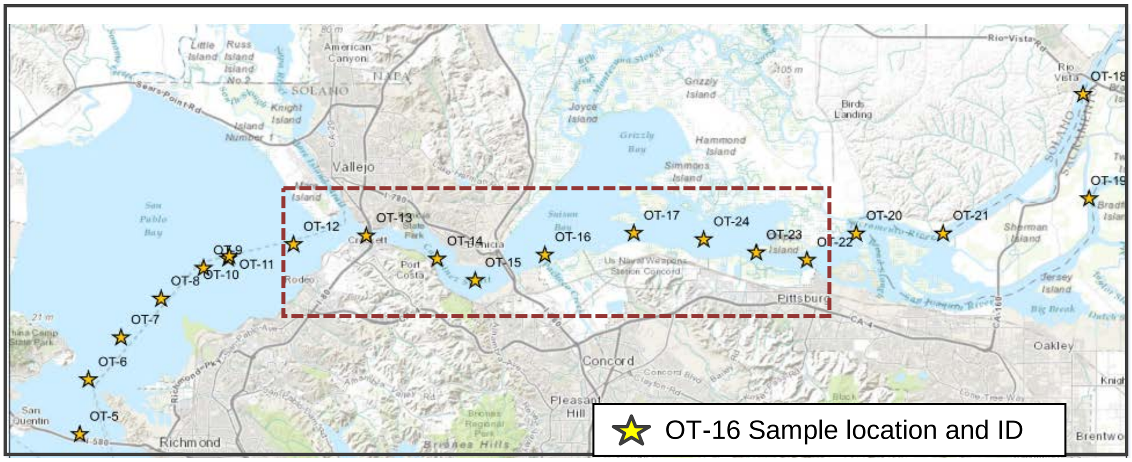


Figure 17: Focused seaward locations for October 2011 transect

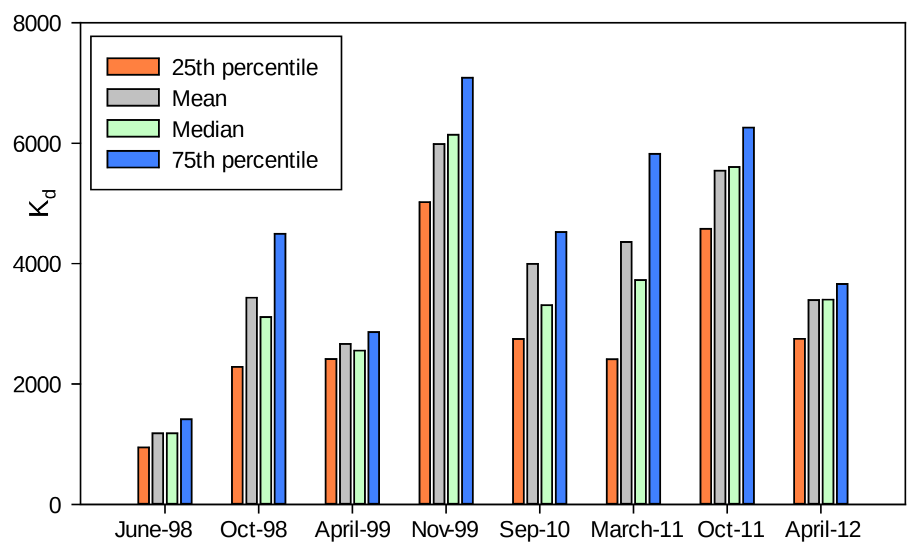


Figure 18: Variability in estimated K_ds in Suisun Bay and Carquinez Strait

Out of the focused seaward data, the 75th percentile and median K_d for each available transect was selected to translate the TMDL tissue target to water column concentrations. Our 75th percentile K_ds range from 1414 to 7089 and, overall, are more conservative than the K_d of 3317, which was used to represent the average conditions in the North Bay by USGS (Presser and Luoma 2013).

The ECoS3 model was run to verify the range of ratios of particulate to dissolved selenium throughout the North Bay. The modeling results confirm that large spatial and temporal variability in selenium partitioning exists, which signifies that even the monitoring data, representing instantaneous conditions after all, may not be adequate to fully describe selenium transformations occurring in a complex ecosystem such as the North Bay. However, the ECoS3-based modeling framework links selenium speciation to specific hydrodynamic regimes reflective of ecological factors making it an effective tool in K_d characterization (Figure 16, Tetra Tech 2010).

The model estimated K_d*s* (particulate/dissolved selenium) at five locations for the period of 1999-2007 were used to estimate the K_d statistics. K_d values generally increased from Suisun Bay to San Pablo Bay and to Central Bay, largely as a result of the organic enrichment of particulates that takes place from the riverine boundary to the ocean boundary. The modeled K_d*s* range from 2000 to just over 17000 L/kg and the 75th percentile K_d for Suisun Bay (5373) closely resembles the value estimated based on the monitoring data. This provides an independent validation for the range of K_d*s* used to determine the protective selenium concentrations in water column.

Calculation of the Allowable Dissolved Selenium Concentration

The calculations of the desirable dissolved selenium concentrations required to achieve the TMDL fish-tissue target were performed for the benthic food web scenario considering fish like sturgeon and Sacramento splittail, which are exposed to selenium and most sensitive. Table 7 shows the specific steps and parameter values applied in the translation model from the TMDL tissue target to water column. The conservative parameter values used throughout the modeling ensures protection of beneficial uses in the Bay and addresses uncertainty in the estimates.

K_d values were obtained from observed water and particulate selenium concentrations over 8 sampling events, and the 75th percentile and median was computed based on multiple measurements made during each event (Table 8). The 75th percentile and median K_d values were used with the translation equation in Table 7 to estimate concentrations that would be protective of clam-eating fish for each of these 8 sampling periods (Table 8). The average allowable concentration based on the 75th percentile K_d is 0.52 μg/L, and based on the median K_d is 0.64 μg/L. Based on the above assumptions we propose a conservative water column target of 0.5 ug/L.

Table 7: Summary of parameters for translation of TMDL tissue target to water column concentration

Methodology steps	Assumptions
Determine target species	Clam eating fish (sturgeon, Sacramento splittail)
Choose toxicity guideline (numeric target) for fish	Numeric Target(s): **8.1** µg/g whole body, dry weight (wb dw); 11.8 µg/g muscle, dry weight
Choose species-specific TTF_{fish} or use default TTF_{fish} of 1.1	$TTF_{generic\ fish} = 1.1$
Identify appropriate food web(s) for selected fish species based on fish-specific diet	Benthic – dominated by *C. amurensis*, with a mixed diet of *C. amurensis (40%) and* crustaceans *(60%)*
Choose TTF_{clams} for invertebrates in selected food web or use default TTF_{clams} for class of invertebrate	$TTF_{C.\ amurensis} = 8.0$ (range 4 – 8) $TTF_{crustaceans} = 1.3$ (range 0.6 – 2)
Choose K_d based on source of selenium and receiving water conditions	75th percentile and median K_{ds} computed from transect data for focused seaward locations
Translation assuming a mixed diet	$\boldsymbol{C_{water}} = \dfrac{TMDL\ target}{[0.4\,\boldsymbol{TTF}_{clam} + 0.6\,\boldsymbol{TTF}_{crustac}]\boldsymbol{TTF}_{fish}\boldsymbol{K}_d}$

Table 8: Water column concentrations protective of clam eating fish

Transect	Jun-98	Oct-98	Apr-99	Nov-99	Sep-10	Mar-11	Oct-11	Apr-12
75th %tile K_d	1414	4498	2861	7089	4525	5825	6263	3663
Modeled selenium concentration µg/L	1.30	0.41	0.64	0.26	0.41	0.32	0.29	0.50
Average allowable concentration for all seasons (75th percentile K_d) **0.52 µg/L**								
Median K_d	1180	3111	2555	6142	3307	3724	5605	3401
Modeled selenium concentration µg/L	1.56	0.59	0.72	0.30	0.56	0.49	0.33	0.54
Average allowable concentration for all seasons (median K_d) **0.64 µg/L**								

Validation of the approach and the parameters used in this modeling was accomplished by comparing forecasted selenium concentrations in sturgeon with field data. Using the default recommended TTF for fish of 1.1 and the typical range of concentrations measured in *C. amurensis* (~9.9 to 12 µg/g: mean / 75th percentile) and assuming selenium concentrations in other food items to be 3 µg/g, we can project concentrations in sturgeon likely to vary from 6.3 to 7.3 µg/g wb dw. Although information on concentrations in the whole-body sturgeon is not available, the modeled range correlates well with selenium levels measured in muscle tissue (1997-2009 average 7.3 µg/g-dw ±4.2(stdev), n=128, Figure 11). The ratio between muscle and whole-body concentrations inferred from regressions in USFWS (2012) indicates that muscle tissue concentrations are likely to exceed those in whole-body by 30 percent or more.

5 SOURCE ANALYSIS – SOURCES AND LOADS

Selenium mainly originates from natural sources such as sedimentary rocks, seleniferous soils, and selenium-rich mineral deposits occurring throughout California. Marine shales of Late Cretaceous period formed by sedimentary accumulation and mineralization of marine particulate matter are particularly rich in selenium (SWRCB 1988). Selenium from these sources could be concentrated and redistributed by geological and biological processes, and by anthropogenic activities. Agricultural management practices leading to selenium enrichment in irrigation drainage water are often considered to be the main cause of surface water contamination in California and the San Francisco Bay Area. Irrigation remobilizes selenium by leaching it from soils originating from marine sedimentary deposits. Weathering and erosion of selenium-enriched sediments may contribute to the elevated selenium levels in nearby streams and groundwater. Fossil fuels, such as coal and crude oil, are naturally enriched with selenium. Therefore, refining and cracking of crude oil, combustion of fossil fuels and solid waste, microbial activity and industrial processes also release selenium to the atmosphere and surface waters.

There are several sources contributing selenium into the North San Francisco Bay. The main sources are inflows from Central Valley watersheds through the Delta and runoff from local tributaries, and industrial and municipal discharges including petroleum refineries. Erosion and sediment transport within the Bay and atmospheric deposition are a small source representing background conditions. Brief descriptions of each source loading contribution and the uncertainty associated with the load estimates are summarized in Table 9. The magnitude of selenium loads and their temporal variability are discussed in the subsequent sections.[6]

During the wet season, riverine sources contribute much larger loads than any other source discharging to the Bay. While there is usually only limited inflow from the San Joaquin River into the estuary, selenium loads increase significantly when water from the River reaches the Bay because of its typically much higher selenium concentrations. Dry season inputs could be important to selenium bioaccumulation due to longer residence times, however, concentrations in the Bay do not change from season to season.

[6] Selenium load assessment presented in the following sections is based on the Source Characterization Report (2008a) prepared by Tetra Tech, Inc., and updated with recent data (2010-13)

Table 9: Sources and loads of selenium in the North Bay

Source		Description	Dominant Selenium Forms	Annual Load [kg][a]
Sources Included in the TMDL	Central Valley watersheds via Delta inflow	Delta inflow consists of flow from the San Joaquin and Sacramento Rivers, and forms the major source of selenium to the Bay. The rivers are also the main source of particulate selenium that provides a pathway to bioaccumulation in benthic organisms. Sacramento R. dissolved selenium represents the regional background levels, they have been consistently low and have remained unchanged over years. San Joaquin R. carries seleniferous agricultural return flows and historically has had much higher concentrations of dissolved selenium. Much of San Joaquin R. flows are currently diverted for agricultural and drinking water uses. Particulate selenium in Delta inflow	**Dissolved Se**: Sacramento River - selenate (25–55%) selenite (5–12%) organic selenide (30–70%) San Joaquin River - selenate (70 – 90%) selenite (5 – 12%) organic selenide (15–18%) **Particulate Se**	**3300** [b] (75^{th} %tile) (<1000 – 7990) **770** (average) (170 -1660)
	Runoff from local tributaries	Runoff from local tributaries contributes the background watershed load and may be a significant natural source of selenium during the wet season.	Speciation assumed to be similar to Sacramento R.	**520** (350 - 840)
	Petroleum Refineries	Refineries contribute the largest load of selenium among point sources discharging to the Bay. The refinery effluent consists almost exclusively of dissolved forms of selenium with selenate, the less bioavailable form, being the dominant species since 1999.	**Predominantly dissolved Se** (98%): selenate (53%) organic selenide (21%) selenite (26%).	**571**
	Municipal and industrial wastewater	Municipal and industrial wastewater effluents generally have low concentrations of selenium and they have not changed over the past 20 years. Total selenium concentrations in the effluent are measured and reported on regular basis.	**Predominantly dissolved Se**: selenate dominates (up to 97%), selenite (1-26%), organic Se (average 41%)	**116**
	Atmospheric deposition	Atmospheric deposition includes both dry and wet deposition directly to the Bay water surface and is considered a very minor selenium source. The numbers presented are an estimate based on the literature.	Wet deposition Dry deposition	**20** <**10**
			TMDL expressed as kg total Se per year	**5300**[c]

[a] Unless noted, loads are expressed as total selenium. Values in bold represent the best estimate, values in parenthesis show the range.

[b] Load estimated using DSM2 model

[c] TMDL load differs from column sum due to rounding

5.1 Selenium Sources

Municipal and Industrial Wastewater Dischargers

Figure 19 shows locations of municipal and industrial facilities discharging treated effluent directly or indirectly to the North Bay. Among them there are 25 municipal wastewater treatment facilities, two minor industrial facilities, and five petroleum refineries.

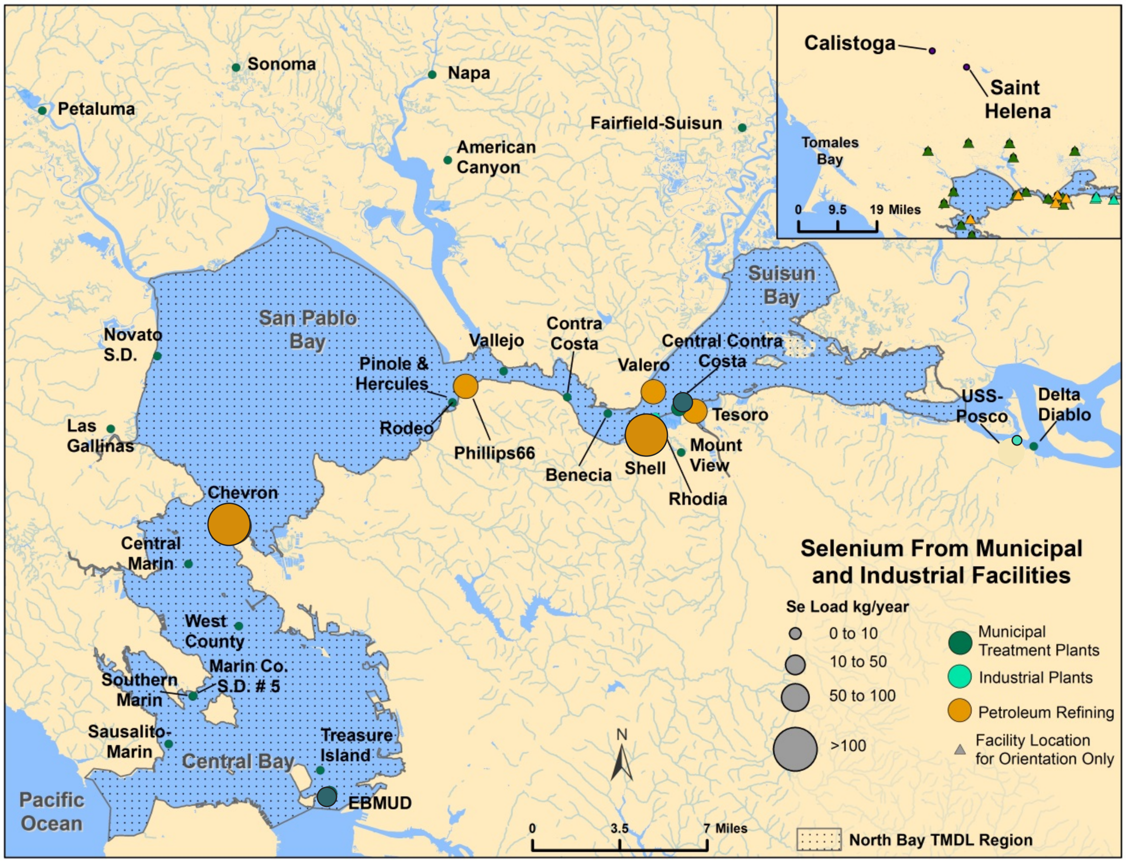


Figure 19: Locations and indicative loads from point sources

North Bay Petroleum Refineries

Petroleum refineries are the largest permitted source of selenium in the North Bay. The total refinery emissions based on the 2008-2013 data are just over 570 kg/yr (Table 10, Figure 20) and have not changed over the last 10 years. The total load from refineries translates to the average daily load of 1.56 kg/day.

Refinery effluent data consist of daily average flow rate and selenium concentration data collected on a weekly basis. Mean selenium concentrations in the refineries' effluent for the last 5 years range from 8.6 µg/L (Tesoro) to 28.9 µg/L (Shell Martinez; Table 10) and are similar or lower than the concentrations reported in previous years (Figure 21). The five petroleum refineries' daily loads were estimated from the daily measurements of flow and the corresponding daily maximum selenium concentrations. The monthly load represents the number of days in the month multiplied by the mean value of daily loads available within the month. The annual load in Table 10 is an average of annual loads calculated over the 5-year record. Current loads are significantly lower than those discharged prior to improvements in refineries wastewater treatment (1,407 – 3,382 kg/yr in 1986 – 1992; Presser and Luoma 2006, Figure 20).

Table 10: Summary statistics of treated effluent from petroleum refineries

Refineries	Time Period	No of samples	Mean	SD	Min	Max	Average Annual Load
			µg/L				kg/year
Chevron	2008-2012	293	12.1	4.2	2.5	47	111
Phillips66	2008-2012	288	25.3	13.2	2.4	75	93
Shell	2009-2013	263	28.9	7.3	9.9	51	244
Tesoro	2008-2012	248	8.6	2.2	4.3	16	60
Valero	2008-2012	307	22.3	7.8	3.5	67.4	63

SD – standard deviation

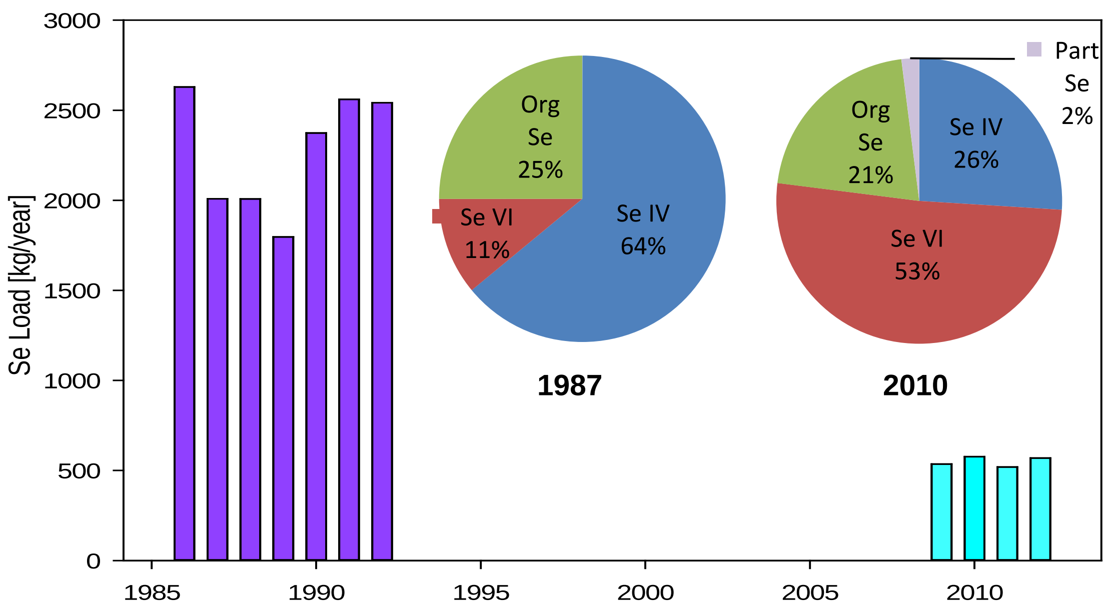


Figure 20: Load reductions and selenium composition in petroleum refinery effluents
(Flow-weighted average of 5 refineries, particulate selenium was not measured prior to 2010)

Daily flow measurements at the refineries indicate some seasonal high flows, likely to be due to stormwater runoff. Despite flow variability, estimated annual selenium loads are relatively constant throughout the years (Figure 22). Similar to the municipal and other wastewater discharges, selenium concentrations in the effluents from the refineries generally do not correlate with flow. Seasonal changes in loads from refineries were evaluated according to dry and wet season. The wet season was defined as October 1 to April 30. The dry season was defined as May 1 to September 30. The daily loads during wet and dry seasons remain at similar levels ranging from 0.12 to 0.59 kg/d, and from 0.17 to 0.68 kg/d, respectively. Overall, the average dry season load per day is lower than the wet season daily load at four refineries. Only at Phillips66 are the daily loads slightly higher during the dry months (0.28 versus 0.24 kg/d), which coincides with the higher proportion of the dry season loads (86 percent of wet season load) discharged by Phillips66 compared to other refineries. On average, dry season loads represent 43 to 73 percent of the wet season loads. Generally, annual load does not appear to be affected by dry versus wet years.

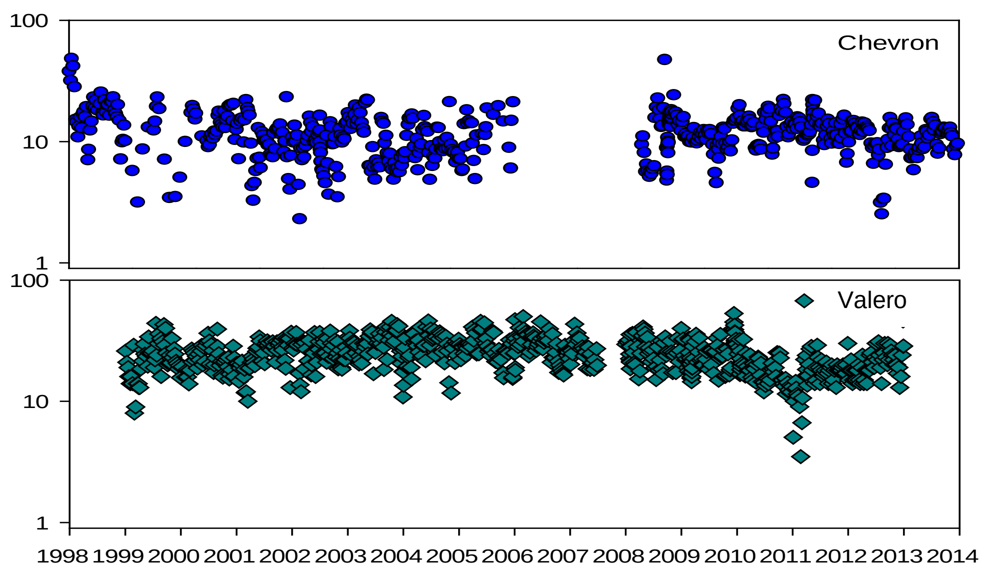
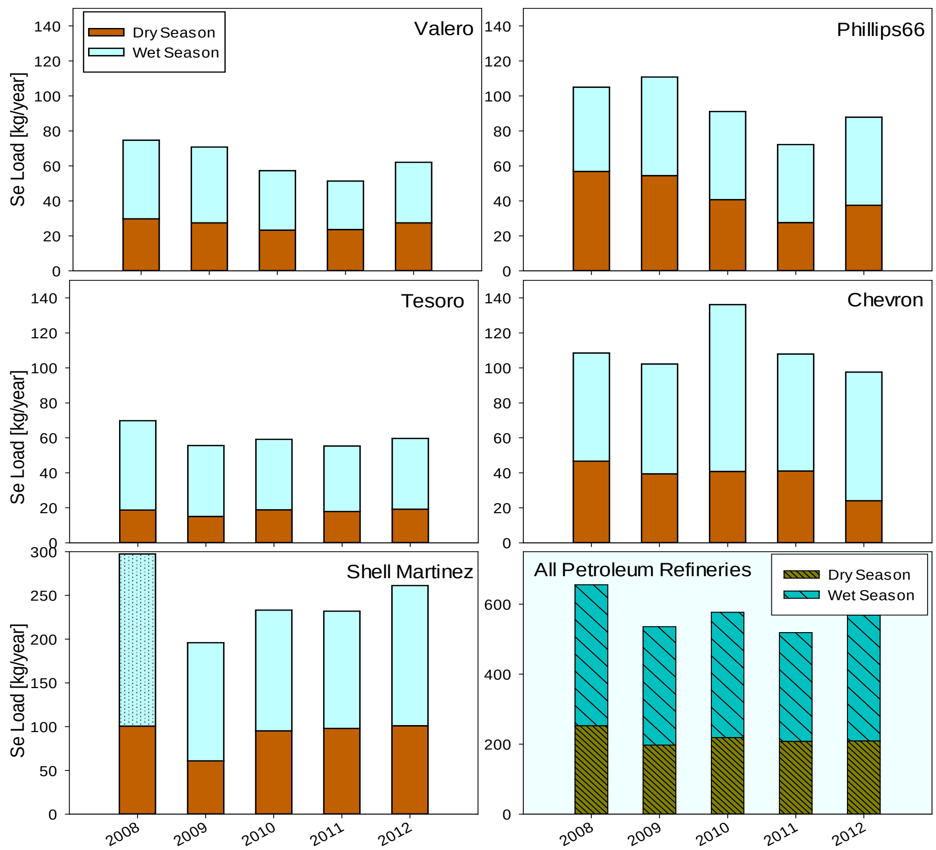


Figure 21: Effluent selenium concentrations in Chevron and Valero refineries

As a result of wastewater treatment improvements in the late 1990s refineries reduced the proportion of selenite, the bioavailable form, in the effluent. Speciation of dissolved and particulate selenium was measured in refinery effluents on a monthly basis from October 2010 through September 2011 (Tetra Tech 2012). The present day effluents consist predominantly of dissolved selenium with particulate selenium forming less than 2 (±2.2) percent of the discharge (Figure 20). When combined together, the average dissolved effluent concentration was 15.9 µg/L and was dominated by selenate (53 percent) and organic selenide (21 percent). Selenite was 26 percent of the total on average, which was slightly higher than the proportion estimated during 1999-2000 sampling (19 percent). The proportion of the bioavailable selenite in refinery effluents continue to show significant improvement with proportion of selenite at only 26 percent in 2010, compared to 64 percent in 1987-1988 (Cutter and Cutter, 2004).



2008 loads from Shell refinery are above average due to problems at the wastewater treatment plant

Figure 22: Dry and wet season selenium loads from refineries from 2008 through 2012

Among particulate selenium species, particulate elemental selenium was dominant with concentrations ranging from 0.01 to 5.7 µg/L (0.34±0.8 µg/L, mean±sd, n=52), followed by organic selenide from 0.01 to 0.3 µg/L (0.1±0.1 µg/L, n=30, ND n=12). Particulate selenite and selenate showed the lowest concentration, generally below 0.06 µg/L (0.03±0.03 µg/L, n=52). Total particulate concentrations generally ranged from 0.03 to 0.6 µg/L (0.25±0.2 µg/L, n=58, (Figure 23:). In all samples, the least bioavailable elemental selenium dominates, comprising up to 99 percent of particulate fraction (69.2±22 percent, n=52).

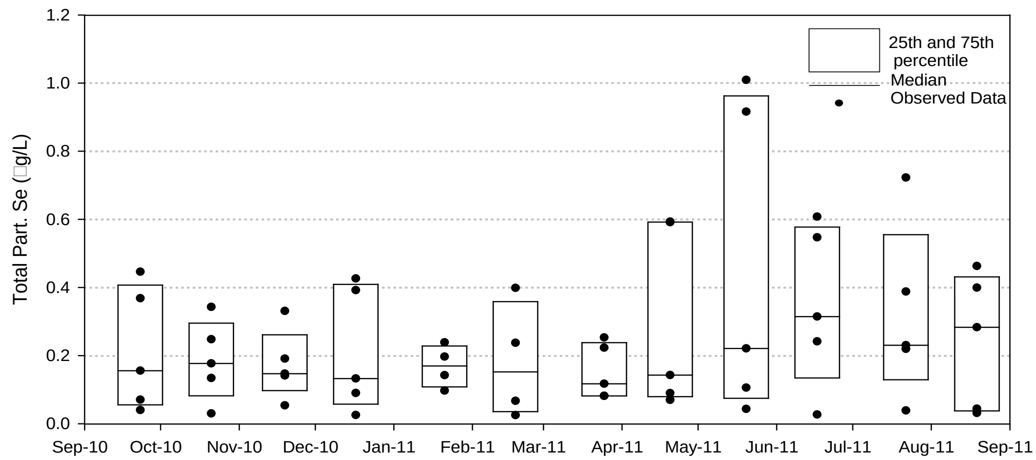


Figure 23: Total particulate selenium concentration in petroleum refinery effluents

Municipal Wastewater Dischargers

On average, all municipal facilities cumulatively discharge into the North Bay approximately 110 kg of selenium per year. The largest selenium load of approximately 30 kg/yr is discharged by East Bay Municipal Utility District (EBMUD), which is due to the large service area and the highest effluent flow, followed by Central Contra Costa Sanitation District (CCCSD) with the load of 17 kg/yr. Both of these facilities measure consistently low selenium concentrations in their effluent that average at 0.3 µg/L. The discharge from the remaining facilities on average does not exceed 3 kg/yr. In general loads from the municipal facilities are small compared to other sources in the North Bay.

Most municipal wastewater facilities discharging to the North Bay and its watershed treat effluent to the secondary level, which includes settling, filtration, and biological treatment. City of American Canyon, Calistoga, Mt. View, and Fairfield Suisun Sewer District provide advanced level treatment, which removes additional solids and, consequently, reduces the amount of particulate selenium in treated effluent.

The average flow from the municipal facilities ranges from less than one million gallons per day (mgd) (City of Calistoga and St. Helena) to almost 70 mgd (EBMUD) with the maximum flow exceeding 150 mgd (EBMUD). Selenium concentrations in treated effluent show low variability, and are generally well below 1 µg/L (Figure 24, Table 11). Average concentrations at the two facilities with the largest discharges, EBMUD and CCCSD, are 0.32(±0.1) µg/L and 0.33(±0.13) µg/L, respectively. These most recent concentrations (2008-2013) are lower than the dissolved selenium concentrations observed by Cutter and San Diego-McGlone (1990) during 1987-1988 effluent sampling (EBMUD: 0.37(±0.10) µg/L, CCCSD: 0.53(±0.11) µg/L).

Generally, average selenium concentrations in effluent are in the range of 0.25 to 0.7 µg/L with a grand mean of 0.44 µg/L.

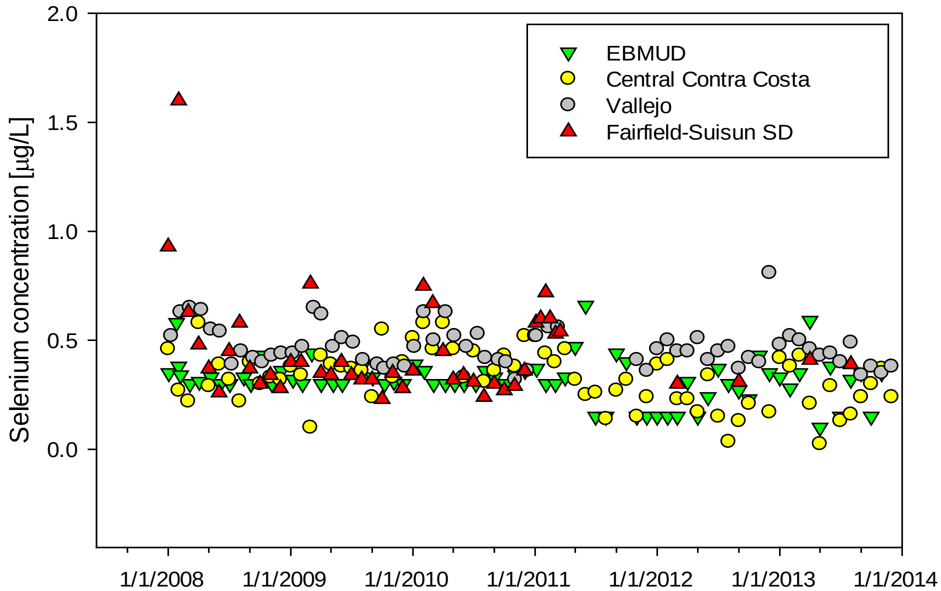


Figure 24: Total selenium concentrations in effluent from selected largest municipal dischargers

Selenium speciation and particulate fraction data are available for five municipal facilities located in the North Bay (CCCSD, EBMUD, Delta Diablo, Fairfield Suisun (FSSD) and Vallejo Sanitation District (VSD); Yee 2012) Particulate selenium forms only a small fraction of the total selenium ranging from 2 percent (FSSD) to 14 percent (VSD). No seasonal patterns or significant differences between the seasons were detected in particulate selenium concentrations in the facilities sampled. However, it has been demonstrated that particulate selenium correlates with total suspended solids, which suggests that solids removal performed by each treatment facility is generally effective at reducing the particulate selenium fraction in the effluent. Overall, most selenium in the effluent from municipal treatment plants is found in the dissolved fraction. Among the dissolved forms, the least bioavailable selenate was the dominant species accounting for up to 97 percent of dissolved selenium in individual samples, averaging (±stdev) 43(±26) percent for all samples together. The organic selenium was often the next most abundant, accounting for up to 77 percent (average 41(±23) percent). Selenite typically accounted for a smaller portion (1 percent to 26 percent, average 11(±8) percent).

Table 11: Summary statistics of selenium concentrations in municipal wastewater effluent

Municipal dischargers	Time Period	No of samples	Selenium Concentrations in Effluent µg/L			
			Mean	S.D.	Min	Max
City of American Canyon	2008-13	72	0.7	0.32	0.19	1.7
City of Benicia	2008-13	67	0.35	0.17	0.15	1.1
City of Calistoga	2010-12	16	0.31	0.09	0.15	0.5
Central Contra Costa Sanitation District	2008-13	71	0.33	0.13	0.13	0.58
Central Marin Sanitation Agency	2008-13	48	0.35	0.35	0.14	1.9
Contra Costa Co. Sanitary District No.5	2009-11	3			0.09	0.76
Delta Diablo	2008-13	109	0.75	0.27	0.41	2.6
East Bay Municipal Utility District	2008-13	73	0.32	0.1	0.23	0.66
Fairfield-Suisun Sewer District	2008-13	46	0.45	0.24	0.23	1.6
Las Gallinas Valley Sanitary District	2008-13	49	0.3	0.17	0.03	0.74
Marin County S.D. no 5	2008-13	68	0.51	0.21	0.21	1.4
Mt. View Sanitary District	2008-13	16	0.36	0.43	0.054	1.64
Napa Sanitation District	2008-13	38	0.41	0.22	0.15	1.2
Novato Sanitary District	2011-13	33	0.45	0.16	0.11	0.74
City of Petaluma	2008-13	34	0.34	0.31	0.017	1.4
City of Pinole	2009-13	11	0.52	0.21	0.28	1
Rodeo Sanitary District	2008-13	5	0.49	0.26	0.25	0.74
Sausalito-Marin City Sanitary District	2008-13	60	0.39	0.21	0.22	1.2
Sewerage Agency of Southern Marin	2008-13	11	0.42	0.21	0.21	0.95
Sonoma Valley County Sanitary District	2013	2			0.45	0.5
City of St. Helena	2006-09	8	0.4		0.23	0.72
Treasure Island	2010-11	21	0.25	0.08	0.07	0.43
Vallejo Sanitation and Flood Control District	2008-13	65	0.47	0.09	0.32	0.81
West County Agency	2008-13	66	0.6	0.51	0.16	2.4
Town of Yountville	2010-13	3	0.26		0.17	0.42

All recent flow and effluent concentration data (2008 – 2013) reported by the municipal facilities as part of their permit and self-monitoring requirements were used to evaluate the average annual selenium loads discharged by each facility (Table 12). Loads were calculated using monthly effluent flow rate expressed as MGD (million gallons per day) and selenium effluent concentrations measured during that month. The load was averaged for the entire period of the available data and expressed in kilograms per year. For data reported below the detection limit, concentrations were assumed to be half of the detection limit. For the facilities with limited number of samples and flow data (e.g. St. Helena, Rodeo Sanitary District, Sonoma Valley County Sanitation District, and Yountville) overall average selenium concentration in all available samples together with the average annual flow were used to estimate loads.

Table 12: Average annual selenium loads from municipal wastewater dischargers

Municipal dischargers	Time Period	Treatment Level	Average Flow	Average Annual Load
			MGD	kg/year
City of American Canyon	2008-13	Advanced	1.57	1.6
City of Benicia	2008-13	Secondary	2.22	1.1
City of Calistoga	2010-12	Advanced	0.82	0.3
Central Contra Costa Sanitation District	2008-13	Secondary	37.9	17.4
Central Marin Sanitation Agency	2008-13	Secondary	4.94	4.0
Contra Costa Co. Sanitary District No.5	2009-11	Secondary	0.02	<0.1
Delta Diablo	2008-13	Secondary	8.08	8.1
East Bay Municipal Utility District	2008-13	Secondary	69	30.0
Fairfield-Suisun Sewer District	2008-13	Advanced	16.8	9.7
Las Gallinas Valley Sanitary District	2008-13	Secondary	4.3	1.2
Marin County S.D. no 5	2008-13	Secondary	0.63	0.5
Mt. View Sanitary District	2008-13	Advanced	1.74	1.1
Napa Sanitation District	2008-13	Secondary	11.93	6.7
Novato Sanitary District	2011-13	Secondary	5.01	2.5
City of Petaluma	2008-13	Secondary	7.17	3.4
City of Pinole	2009-13	Secondary	2.87	2.2
Rodeo Sanitary District	2008-13	Secondary	0.61	0.4
Sausalito-Marin City Sanitary District	2008-13	Secondary	3.72	1.9
Sewerage Agency of Southern Marin	2008-13	Secondary	2.51	1.4
Sonoma Valley County Sanitary District	2013	Secondary	1.77	2.1
City of St. Helena	2006-09	Secondary	0.63	0.4
Treasure Island	2010-11	Secondary	0.35	0.1
Vallejo Sanitation and Flood Control District	2008-13	Secondary	10.11	6.7
West County Agency	2008-13	Secondary	9.88	7.9
Town of Yountville	2010-13	Secondary	0.43	0.2

Industrial Wastewater Dischargers

Loads from industrial facilities in the North Bay are minor compared to other sources, and average about 5 kg Se /yr (Table 13). C&H Sugar Co. has selenium in their discharge, however, concentrations in intake water used for cooling and industrial applications are equal to or higher than the concentrations in the discharge, therefore, this facility does not contribute a net load to the North Bay and is not included in Table 13, which lists quantified selenium loads from industrial wastewater dischargers.

Table 13: Estimated selenium loads from industrial wastewater dischargers in the North Bay

Industrial Facilities	Daily load g/day	Annual load kg/yr
Solvay (formerly Rhodia, Inc.)	1.3	0.5
USS-Posco Industries	12.6	4.5
Total	***13.9***	***5.0***

Urban and Non-Urban Runoff from Local Tributaries

Local tributaries (streams that discharge directly into the North Bay) (Figure 25), contribute background selenium loads due to the presence of seleniferous soils in their watersheds. Although these tributaries generate less than 4 percent of the total freshwater flow to the Bay, the relative proximity to the Bay, could amplify the delivery rate. McKee *et al*. (2003) have found that sediment export from small local tributaries averages approximately 100 t km^{-2}, which is much higher than the recent exports from the Central Valley (~14 t km^{-2}). The average estimated load is 520 kg/yr.

Real time flow measurements and selenium concentrations in runoff from local tributaries are limited, thus the load assessments based on the available data are associated with large uncertainty. Therefore, to provide a better insight into the variability and magnitude of loads delivered into the North Bay, we used three methods to evaluate selenium tributary loads. The available data, calculation methods, and assumptions are summarized below.

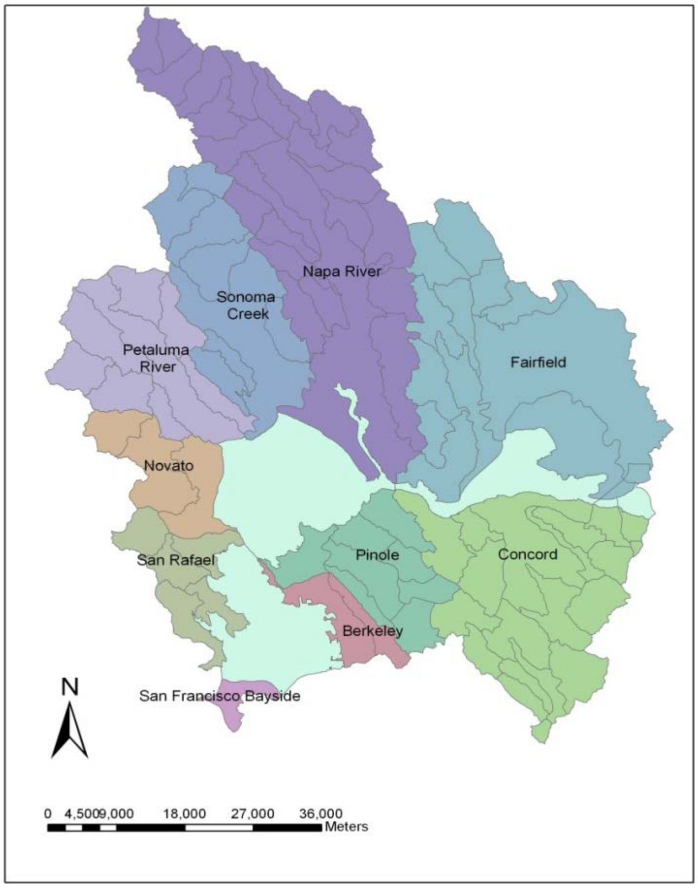


Figure 25: Hydrological areas surrounding the North Bay

(Source: San Francisco Bay Institute)

The available selenium concentration data for tributaries are limited and highly variable. The locations, sources and time span of the available data are shown in Table 14. The Surface Water Ambient Monitoring Program (SWAMP) monitored selenium in five tributaries in the North Bay during two sampling seasons in 2001-02 and 2003-04. Selenium concentrations of 0.18–3.39 µg/L (median 0.94 µg/L) were measured during dry season, and 0.39–3.14 µg/L (median 0.90 µg/L) during wet season. Total selenium concentrations as high as 1.7 and 4 µg/L, were observed in Petaluma River during the wet and dry season of 2003-04. Table 14 shows data available for the most downstream locations within the tributaries draining into the North Bay. These sites are considered indicative of the conditions within the entire watershed and therefore most suitable for the purpose of load estimates.

Table 14: Selenium concentrations at downstream locations by season

Water Body	Site	Season	Year	Total Se [µg/L]	Source
San Pablo Ck.	206SPA020	Spring	2001-2002	2.74	SWAMP [a]
		Dry		1.6	SWAMP
Suisun Ck.	207SUI020	Spring	2001-2002	0.9	SWAMP
		Dry		0.32	SWAMP
		Wet	2012	0.25	Tetra Tech [b]
Wildcat Ck.	206WIL020	Spring	2001-2002	0.39	SWAMP
		Dry		1.33	SWAMP
Kirker Ck.	KIR020	Wet	2003-2004	1.26	SWAMP
		Spring		1.3	SWAMP
		Dry		2.5	SWAMP
Mt Diablo Ck.	MTD010	Wet	2003-2004	2	SWAMP
		Spring		0.4	SWAMP
Petaluma R.	San Antonio Ck	Wet	2003-2004	1.3	SWAMP
		Spring		0.2	SWAMP
	Petaluma R.	Wet	2003-2004	0.93	SWAMP
		Spring		1.3	SWAMP
		Dry		4	SWAMP
	Petaluma R.	Wet	2012	0.17	Tetra Tech
Walnut Ck.		Wet	2010-2011	2.69	BASMMA [c]
		Wet	2012	0.58	Tetra Tech
Pinole Ck.		Wet	2010-2013	2.77	BASMMA
		Dry		6.45	BASMMA
		Wet	2012	0.79	Tetra Tech
Napa R.		Wet	2012	0.14	Tetra Tech
Novato Ck.		Wet	2012	0.11	Tetra Tech
Santa Fe Ch.		Wet	2010-2011	0.28	BASMMA
Average		***Wet/Spring***		***1.03***	
		Dry		***2.70***	
		All Data		***1.41***	

[a] SWAMP selenium concentration data (SFBRWQCB 2007a, SFBRWQCB 2007b)
[b] Tetra Tech (2012)
[c] BASMMA (2013)

The Bay Area Stormwater Management Agencies Association (BASMAA) collected selenium concentration data during a 1988-1995 monitoring study. Sixteen sampling sites in this assessment were located in Alameda County and two sites were located in Contra Costa County. The monitoring program focused on measuring concentrations of pollutants in stormwater and was designed to determine pollutant loads in stormwater runoff dominated by different land uses (BASMAA 1996). Automated monitoring equipment was placed within the stormwater conveyance system to record runoff and to collect flow-weighted composite water samples. These monitoring stations received runoff from areas that were not larger than 1.5 square miles. Samples were also collected from selected waterways, including San Lorenzo, Alameda, Walnut and Dry Creeks, to evaluate the quality of receiving waters during storm events. The waterway drainage areas varied in size from approximately 10 square miles (Dry Ck) to over 600 square miles (Alameda Ck). Selenium concentrations reported by BASMAA are generally lower than values reported in subsequent SWAMP studies. Median concentrations were 0.40 µg/L during dry weather (n=7) and 0.33 µg/L for storm event sampling (n=28). By land use, median selenium concentrations were 0.29, 0.35 and 0.30 µg/L for residential, open and industrial locations, respectively.

In 2012 selenium was analyzed in a small number of urban creeks including Santa Fe Channel, Pinole and Walnut Creek (BASMMA 2013). The highest average concentrations, ranging from 2.77 µg/L (wet) to 6.45 µg/L (dry), were detected at a site near the stormwater pump station in Richmond. The high concentrations measured during the dry period potentially resulted from the high content of suspended sediments in the samples and they may not be fully representative of stormwater concentrations. Subsequent wet season sampling in 2013 and 2014 showed much lower concentrations (0.24 to 0.74 µg/L), which were in agreement with data collected in March 2012 by Tetra Tech (2012), in six creeks (including Walnut and Pinole Creek), with concentrations in the range from 0.11 to 0.79 µg/L.

Load Estimates Using Simple Model with All Data (Method 1)

This approach employs a simple model to predict runoff volumes, and the concentration data collected at the local tributaries to compute loads. The volume of runoff is predicted using empirical runoff coefficients for discrete land use categories, rainfall, and the area of each land use. Pollutant loads are then calculated as the product of mean pollutant concentrations and runoff depths over specified period of time. The validity of the runoff model was tested and compared against local data by Davis *et al*. (2000) with good result.
The contaminant load is calculated as follows:

$$Load = \sum_{j=1}^{n} (v_j * i * A_j) * C_{ave}$$

Where: ***v*** is runoff coefficient for land use *j*; ***i*** is the average rainfall for a hydrologic unit, and $\boldsymbol{A_j}$ represents the area of land use *j* in the hydrologic unit. $\boldsymbol{C_{ave}}$ is the average measured contaminant concentration for the hydrologic unit.

Runoff volumes calculated by Davis *et al*. (2000) and concentrations in Table 14 were used to estimate loads from each watershed surrounding the North Bay (Table 15, Figure 25). Selenium was sampled during wet, spring, and dry seasons at four out of ten hydrological areas surrounding the North Bay. For those areas where site-specific data were not available, the average wet/spring concentration from all available monitoring locations was used to estimate loads. The average annual load of total selenium from local tributaries to the North Bay exceeds 500 kg/yr, with the Concord and Fairfield watersheds identified as the largest sources. Higher total selenium loads from these watersheds are most likely due to larger watershed areas and high annual runoff.

Table 15: Runoff and selenium loads from local watersheds

Hydrologic Area	Total Annual Runoff (Mm^3/yr)	Sampling Locations	Mean Total Se Concentrations (µg/L)[1]	Total Se Load (kg/yr)
San Rafael	56		1.03	57.4
Berkeley	25		1.03	25.6
San Francisco-Bayside	8.8		1.03	9.0
Novato	47	Novato Ck.	0.11	5.2
Petaluma River	60	Petaluma R./ San Antonio Ck.	0.78	46.8
Sonoma Creek	68		1.03	69.7
Napa River	180	Napa R.	0.14	25.2
Pinole	35	Wildcat, San Pablo, Pinole Ck./ Santa Fe	1.39	48.8
Fairfield	129	Suisun Ck.	0.58	74.2
Concord[2]	106	Mt. Diablo/Walnut Ck.	1.42	150.3
Concord[3]	6.7	Kirker Ck.	1.28	8.6
Total	***721.5***			***520.8***

[1] 1.03 µg/L is the mean concentration of all wet/spring samples

[2] Concord area: subunits 220731, 220732, 220733 / [3] Concord area: subunit 220734

These large watershed loads expressed on a per unit area basis do not differ significantly from other drainage areas. It is the most developed and highly urbanized watersheds of San Rafael, Berkeley and San Francisco Bayside that contribute on average approximately 3 grams Se per hectare (0.8 kg mi^{-2}), while Petaluma, Napa and Fairfield generating less than 1 grams per hectare (0.3 kg mi^{-2}).

Runoff in the Bay area is governed by the inter-annual variability in rainfall, which subsequently affects the magnitude of pollutant loads. The estimates of the 10th and 90th percentiles of rainfall could be indicative of load range for dry and wet years respectively. Davis *et al*. (2000) evaluated rainfall variability in the Bay area for the period of 1961-1990. Taking into account these rainfall values and assuming an average selenium runoff concentration of 1.03 µg/L (Table 14), the load of selenium from local tributaries could vary from 332 kg in a dry year to 844 kg in a wet year.

Load Estimates Using Available Measured Flow and SWAMP Data (Method 2)

Long-term average monthly flow measured by USGS and the available seasonal selenium concentrations were used to estimate long-term average selenium loads at available gauging stations. Loads were calculated by multiplying flow and concentrations data for the same river. For tributaries without observed selenium concentrations, the overall average wet and/or dry concentration for all the North Bay sites was used (Table 14).

Long-term average monthly flow records at the USGS stations indicate that the majority of the flow is discharged during the wet season defined as October 1 through April 30. The flow during the dry season (May 1 to September 30) amounts to only a small fraction of the wet season flow (0.2 – 3.5 percent) with the exception of Walnut Creek and Pinole Creek for which the dry season flows could reach 13.1 percent and 5.8 percent of the wet season flows, respectively. Similarly, the majority of the load is delivered to the Bay during the wet season. Figure 26 shows a typical monthly pattern of selenium loads from representative tributaries in the North Bay. The highest annual load was estimated for the gauging station on Sonoma Creek at Aqua Caliente (70.5 kg/yr) followed by Walnut Creek at Concord (68.4 kg/yr). Dry season loads are small and average between 0.3 and 15.0 percent of the wet season loads for 6 of the 8 gauging locations (Table 16). A scaling factor based on the annual areal loading was used to extrapolate loads from the gauging location to the entire watershed area for each tributary. An areal loading from a nearby watershed was applied for the hydrological areas without data (e.g. San Rafael, Fairfield).

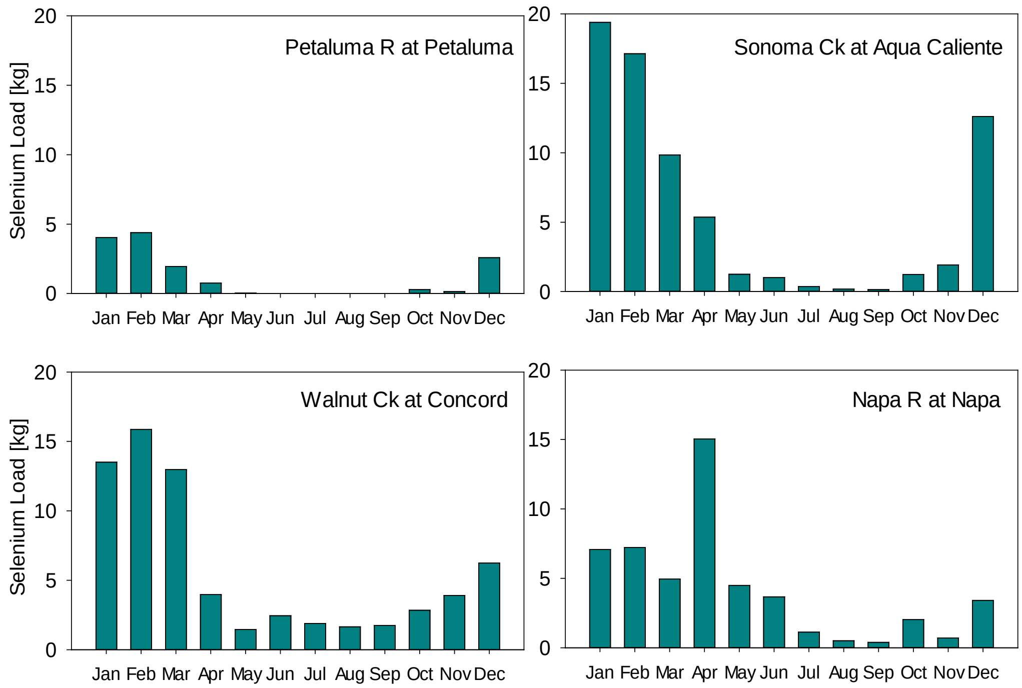


Figure 26: Average long-term monthly selenium loads at selected gauging locations

Table 16: Summary of selenium loads at the USGS gauging stations

	USGS Gauging Stations							
	11459500 Novato Ck at Novato	11459300 San Antonia Ck nr. Petaluma	11459000 Petaluma R. at Petaluma	11458500 Sonoma Ck at Agua Caliente	11458000 Napa R. nr. Napa	11181400 Wildcat Ck at Richmond	11183600 Walnut Ck at Concord	11182100 Pinole Ck at Pinole
Drainage area (mi^2)	17.6	28.9	30.9	58.4	218	8.7	85.2	10
Dry season load (kg)	0.6	< 0.1	<0.1	3.0	10.2	0.1	9.2	0.3
Wet season load (kg)	2.0	19.0	14.1	67.5	40.4	4.7	59.3	4.9
Dry as wet %	28.2	0.3	0.4	4.4	25.2	2.4	15.4	5.6
Total Load (kg/year)	2.6	19.1	14.2	70.5	50.6	4.8	68.5	5.2
Areal load (kg/mi^2)	*0.15*	*0.66*	*0.46*	*1.21*	*0.23*	*0.55*	*0.80*	*0.52*

Estimated total selenium loads for the North Bay by hydrological area are summarized in Table 17. The total selenium load calculated using the available USGS flow data is 800 kg/yr and is higher than the estimates based on modeled runoff described as Method 1. Once again, a large portion of the estimated total tributary load originated from hydrological areas without concentration data (e.g. Sonoma or Fairfield). Due to the lack of selenium concentrations for these two areas, an overall mean concentration of the whole North Bay tributaries was used to compute loads. Thus, these estimates are highly uncertain. Concentrations measured in Napa and Petaluma Rivers in 2012 (0.14 - 0.17 µg/L) were significantly lower than those measured in Petaluma River by SWAMP in 2003-2004 (0.2 – 4.0 µg/L), which resulted in subsequent reduction of the estimated load in Napa River.

Table 17: Estimated wet and dry season loads from local tributaries (*Method 2*)

Hydrological Areas	Area (mi^2)	Dry (kg)	Wet (kg)	Total Load (kg/yr)
San Rafael	60.9	2	7.1	9
Berkeley	33.8	0.4	18.3	18.7
San Francisco Bayside	11.1	0.4	1.3	1.6
Novato	71.0	2.3	8.2	10.6
Petaluma	145.8	0.3	66.7	67
Sonoma	165.9	8.4	191.9	200.3
Napa	362.1	16.9	67.2	84
Pinole	58.9	1.6	28.8	30.4
Fairfield	339.0	36.4	235.9	272.3
Concord	250.3	26.9	174.2	201.1
Total	***1498.8***	***96***	***800***	***896***

Land Use-Specific Loads with Modeled Runoff and Concentration Data from BASMAA and SWAMP Studies (Method 3)

This assessment focused on evaluation of selenium loads generated by individual land uses in each hydrologic area. The method employs the simple model to estimate stormwater runoff associated with each land use within the drainage area and land use distribution (see Method 1, Davis *et al.* 2000). However, concentrations are calculated differently. The model links pollutant concentrations to rainfall and land use allowing for evaluation of potential differences in generated loads between years of different rainfall and types of land uses. It is assumed that mass loads are generated predominantly from diffuse sources and are representative of a long-term average runoff. As such, loads generated during dry weather conditions and resulting from, for example, bank erosion or groundwater inflows, are not well represented in the assessment. Moreover, degradation or adsorption of pollutants while they are being transported downstream is not explicitly accounted for. However, this approach is widely accepted and tested against measured data with good results.

Loads are estimated for five broad land use categories (open space, agricultural, residential, industrial and commercial) based on estimated runoff from each land use type and land-use specific mean selenium concentrations. In this assessment, urban land use includes industrial, commercial and residential areas. The "best estimates" of runoff coefficients and the mean selenium concentrations indicative of a particular land use are shown in Table 18. Land use specific concentrations were derived from BASMAA (1996) and SWAMP studies (SFBRWQCB 2007a, b). Concentrations for agricultural land uses were assumed to be the same as for open space. Due to the differences in concentrations reported by the two monitoring programs, values from the BASMAA project were used as the lower bound of concentrations from local tributaries, while SWAMP data were used as the upper bound.

Table 18: Land use specific runoff coefficients and mean selenium concentrations

	Land Use					Source
	Residential	Commercial	Industrial	Agricultural	Open Space	
Runoff coefficient (best estimate)	0.35	0.9	0.9	0.1	0.25	Davis *et al*. (2000)
Se conc. (low) µg/L	0.36	0.58	0.58	0.50	0.50	BASMAA (1996)
Se conc. (high) µg/L	1.55	1.55	1.55	0.85	0.85	SWAMP

Compiled from Tetra Tech 2008a

The estimated loads range from 354 to 838 kg/yr depending on the mean concentration data used (Table 19). Open space and residential areas are among the major contributors of selenium (301 and 250 kg/yr, respectively) mainly because they occupy a large proportion of every watershed.

Many of the watersheds surrounding the North Bay experience a high level of urbanization. For the purpose of this assessment, urban areas combine residential, industrial and commercial uses and account for more than 50 percent of drainage areas in Pinole, San Rafael, Concord, Berkeley and San Francisco Bayside. The estimated runoff from all urban areas is 316.8 Mm^3yr, which is approximately 44 percent of the total runoff. The loads from urban areas estimated from the SWAMP concentration data exceed 490 kg/yr, or 59 percent of the loads from all land use types. When BASMAA concentrations data are used, the loads are reduced to 148 kg/yr, or about 43 percent of the total load from all land use areas. The land use specific loads for each hydrologic area are shown in Table 19.

Table 19: Loads derived from land use composition in local tributaries

Hydrological area	Land Use Load (kg/yr)					Total Load (kg/yr)
	Residential	Commercial	Industrial	Agricultural	Open Space	
San Rafael	42.4	17.4	2.2	0.0	13.6	*76*
Berkeley	14.4	10.4	11.7	0.0	0.9	*37*
San Francisco Bayside	4.8	8.3	0.4	0.0	0.0	*14*
Novato	19.2	15.1	2.2	1.7	18.4	*57*
Petaluma River	19.7	3.6	7.2	7.7	26.4	*65*
Sonoma Creek	13.7	4.4	4.4	9.7	36.3	*69*
Napa River	40.1	30.9	10.3	15.1	97.3	*194*
Pinole	15.9	6.2	14.9	0.0	9.3	*46*
Fairfield	18.8	20.3	16.1	11.5	67.0	*134*
Concord	60.7	30.5	24.6	1.1	31.6	*149*
UB[1] Total Load (kg/yr)	***250***	***147***	***94***	***47***	***301***	***838***
LB[2] Total Load (kg/yr)	*58*	*55*	*35*	*28*	*178*	*354*

UB[1] Load estimated using the upper bound mean selenium concentrations from the SWAMP data
LB[2] Load estimated using the lower bound mean selenium concentrations from the BASMAA data

Despite observed variability, Methods 1 and 3 provide similar results that are generally lower than those of Method 2 with the exception of the smallest and most urbanized drainage areas, such as Pinole, Berkeley or San Rafael (Figure 27). All three methods show similar load estimates for the highly urbanized drainage areas. Method 3 attempts to increase the resolution of load estimates. All calculation methods show that one of the largest loads is generated by the Fairfield and Concord areas, for which the data are sparse and highly variable. This may suggest that the load estimate is subject to even greater uncertainties. Concurrently, it can be seen that selenium generation rates for Fairfield and Concord resemble other tributaries with similar land use composition (Figure 27).

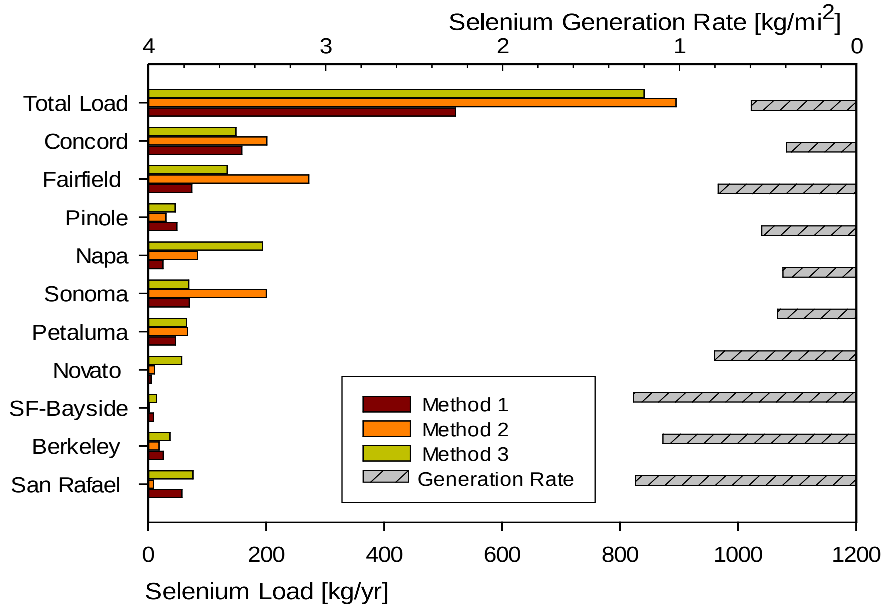


Figure 27: Comparison of load estimates from local tributaries using different calculation methods

(selenium generation rates for each drainage area calculated with Method 3)

The methods used to determine selenium loads from local tributaries into the North Bay take into account underlying data limitations, year-to-year and seasonal variability, and uncertainties in flow calculations. All these uncertainties are reflected in the estimated selenium load, which according to the best available information could range from 354 to 838 kg/yr. No anthropogenic sources of selenium have been identified in urban and non-urban runoff. Based on available scientific understanding the long-term selenium load from tributaries is estimated as 520 kg/yr (Method 1).

Loads from San Joaquin and Sacramento Rivers Delivered via Delta

Sacramento and San Joaquin watersheds are the single largest source of selenium into the North Bay and are estimated to deliver as much as 8000 kg of selenium in a wet year. Selenium loads discharged from these watersheds remain highly variable despite the water storage and extensive flow management taking place in the Delta. Changing patterns of precipitation and runoff together with water diversions and complex interactions occurring at the Delta – Bay interface add to the difficulties in estimating the loads. The relative flows from the rivers and other components of the Delta water budget for an average flow year are depicted in Figure 28.

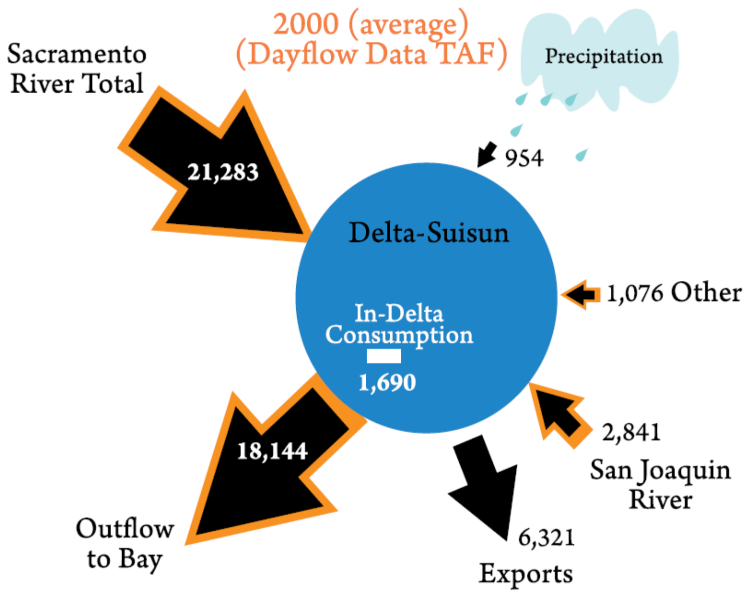
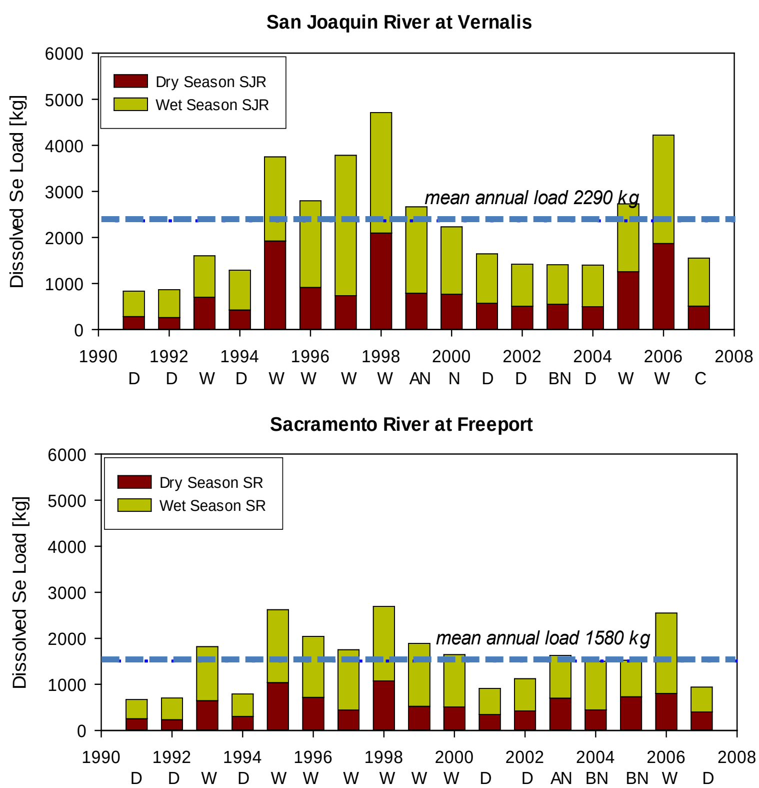


Figure 28: Water balance in the Delta for an average flow year 2000
Flow in thousand acre-feet (*From URS 2007*)

Despite San Joaquin River inflows to the Delta being an order of magnitude smaller than those of Sacramento River, San Joaquin River selenium loads are consistently higher because the San Joaquin conveys Se-enriched agricultural drainage from the Central Valley, resulting in elevated selenium concentrations (0.57±0.32µg/L dissolved selenium). Still, because of diversions and reverse flows in the Lower San Joaquin River, much of the agricultural drainage does not reach the lower estuary. This, however, may change in the near future due to improvements and changes being considered in the Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary (Bay-Delta Plan) and the Bay Delta Conservation Plan/California Water Fix (BDCP). The State Water Board has proposed to increase environmental flows in the Lower San Joaquin River to better protect fish and wildlife beneficial uses, which could result in more San Joaquin River flow, with higher ambient selenium concentrations reaching the Delta and the North Bay. In addition, implementation of various construction and restoration alternatives through the BDCP may also affect selenium balance in the North Bay. By altering the flow patterns and mixing of different water sources, the BDCP alternatives have the potential, albeit small, of increasing selenium water column concentrations in the North Bay. Sacramento River selenium concentrations are much lower (0.09±0.03µg/L dissolved selenium) and more typical of background concentrations in the region.

Three methods were used to estimate the relative contribution of the Sacramento and San Joaquin rivers to the Delta and to examine seasonal and annual load patterns from the Delta to the North Bay. The first method calculates selenium load discharged through the Delta using average dry and wet season concentrations measured at the two RMP stations (BG20 and BG30) above Mallard Island and the tidally corrected net Delta outflow generated by the Dayflow program. This approach was used in the past to estimate various pollutant loads from Central Valley to the Bay (e.g. see Davis *et al.* 2000).

The second method uses dissolved selenium concentrations measured by Cutter and Cutter (2004) in the Sacramento River at Freeport and data collected in the San Joaquin River at Vernalis to estimate individual loads contributed by both rivers. Figure 29 illustrates seasonal and annual variability in the rivers' loads. A "Delta removal constant" of 60 percent, similar to the one described in Meseck (2002), is then applied to the San Joaquin River load to account for complex interactions and the likely selenium losses in the Delta.



Year type: D - dry; W – wet; AN – above normal; BN – below normal; C - critical

Figure 29: Estimates of dry and wet season riverine loads

In the third method selenium loads from the Central Valley through the Delta are determined by estimating loads from the two rivers as described above, and subtracting the load lost to the diversion of much of San Joaquin flow through the aqueducts. This last approach is particularly effective for examining relative selenium load contributions of the two rivers to the North Bay. The explanation of the load calculation methods, the concentration data, and load estimates are described in detail in Tetra Tech (2008a).

Most recently, selenium loads from the Delta were reevaluated using the Delta Simulation Model II or DSM2 (Tetra Tech 2014). DSM2 was run in a fingerprinting mode to predict the composition of the flow in Sacramento River at Rio Vista, San Joaquin River at Antioch, and at Mallard Island (Figure 30). The simulated composition of water in Rio Vista is almost entirely comprised of the flow from Sacramento River. The San Joaquin River flow at Antioch combines inputs from Sacramento River, tidal inputs from the Bay, and east side tributaries, as well as a detectible inflow from San Joaquin River, which becomes more pronounced (exceeding 50 percent of volumetric flow) during the wet years. The simulated flows from different sources and the USGS dissolved selenium data measured at Freeport and Vernalis (mean 0.095 µg/L, n=82; mean 0.568 µg/L, n=84) for the period of 2007 through 2014 were used to calculate the loads at the above locations. For this assessment the observed concentration data were linearly interpolated between the sampling dates. The sum of the loads from Rio Vista and Antioch represents the estimate of selenium inputs to the North Bay (Figure 31).

Figure 30: Locations of DSM2 model outputs

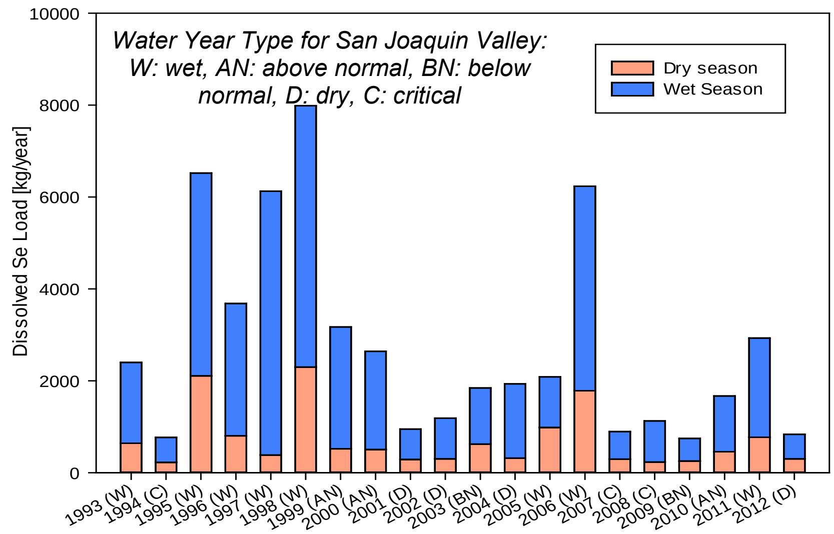


Figure 31: Loads of dissolved selenium from Sacramento and San Joaquin watersheds by water year

Based on the dissolved selenium concentrations only, the estimated riverine loads range between 670 – 2690 kg/yr for the Sacramento River at Freeport, and 840 – 4710 kg/yr for the San Joaquin River in Vernalis and average annual load is 1577 kg/yr and 2289 kg/yr, respectively. Dry season loads for both rivers on average do not exceed 40 percent of the annual load (Figure 31). The annual loads also vary with water years. For example the San Joaquin River annual load may be higher than 4000 kg/yr during wet years (e.g. 1998, 2006) and less than 900 kg/yr in dry years (e.g. 1991, 1992). However, selenium loads that reach the North Bay through the Delta are likely to be more affected by flow diversions and water management than by the overall hydrologic conditions. Table 20 shows a summary of load estimates using different calculation methods and data sets.

Estimates of dissolved selenium load originating from the Central Valley watersheds using the “Delta removal constant”, evaluation of selenium export through the aqueducts, or contribution of different watershed sources through the DSM2 model are very similar and on average range between 2500 and 2800 kg/yr. However, the mixing and hydrodynamic processes in the DSM2 model formulation provide for more sensitivity and better representation of seasonal patterns and contributions from San Joaquin River to the North Bay. For example, the San Joaquin River contribution can be elevated during the wet months of wet years, which could be observed at Mallard Island, while during dry years the loads from the San Joaquin River to the North Bay are very small compared to the loads from Sacramento River. This is consistent with the observations of high selenium concentrations in

January 2005 and 2006, which were reported by David *et al*. (2012), and likely reflects the high San Joaquin contribution during that period. The loads to the North Bay estimated from DSM2 flow simulations could be as low as 744 kg/yr during below normal and critical dry years, and could exceed 6000 kg/yr during wet years (e.g. 1998 – 7989 kg/yr, 2006 – 6236 kg/yr, Figure 31).

Table 20: Dry and wet season loads to the North Bay from the Central Valley watershed and tributaries

Source	Average Se Load [kg]			Assumptions and data used
	Dry	Wet	Annual	
Delta outflow	1007	2931	3938	Total Se load (RMP data, 1994-2006); *Method 1*
Delta outflow	910	1583	2493	Dissolved Se load, 60% removal constant for SJR; *Method 2*
Sacramento River at *Freeport* San Joaquin River at *Vernalis*	564 863	1013 1426	1577 2289	Dissolved Se load (1993-2003 concentration data from Cutter and Cutter, 2004)
Export through aqueducts Delta outflow	665 856	842 1840	1506 2596	Dissolved Se load (1993-2003 concentration data from Cutter and Cutter, 2004) *Method 3*
Sacramento River at *Rio Vista* San Joaquin River at *Antioch*	476 227	1405 678	1881 905	Dissolved Se load (concentration data from Cutter and Cutter, 2004); *DSM2*
DSM2 Delta outflow	778	2709	3298	75th percentile dissolved Se load (concentration data from Cutter and Cutter, 2004; Tetra Tech 2014)

To account for particulate selenium load we used the annual suspended sediment data at Mallard Island for water years 1995-2003 (McKee *et al.* 2006) and limited particulate concentration data from both rivers (Doblin *et al.* 2006). For the range of reported suspended sediment loads from 0.26 Mt/y (2001) to 2.6 Mt/y (1995) and the average particulate concentration (n=10) of 0.64 µg/g, the estimated particulate load varies from approximately 170 to 1660 kg/yr and the average annual load is 768 kg/yr. The total average selenium load calculated as a sum of particulate and dissolved loads corresponds well with the first assessment method of total selenium load based on the RMP data and tidally corrected flow, which estimated the average total selenium annual load from the Central Valley watershed at 3938 kg/yr (Table 20).

The three assessment methods provide independent validation of load estimates to the North Bay. Considering the complexity of the Bay-Delta system, the selenium loads computed with each method are fairly consistent. Method 1 with the different set of concentration data and flow, and DSM2 ascertain that the average dissolved and particulate loads are accurate and in general do not exceed 3300 kg/yr (75th percentile of DSM2 load). However, a large interannual variability could be expected depending on the magnitude of flow, water exports throughout the aqueducts, and hydrologic conditions in the Delta.

Direct Atmospheric Deposition

Atmospheric deposition of selenium occurs in 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 (USEPA 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 (Tetra Tech 2008a).

Dry and wet deposition of selenium has not been measured in the San Francisco Bay and estimates were made using data from other studies. Based upon other studies (USEPA 2002), however, it is likely that atmospheric deposition represents only a small insignificant load. 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 study are in the range of 0.07- 0.17 µg/L (USEPA 1996).

Assuming selenium concentrations of 0.07-0.4 µg/L, an approximate annual rainfall of 450 mm/yr, and the water surface area of 648 km^2 in the North Bay (including Central Bay), direct wet deposition of selenium is in the range of 20.4 – 116.6 kg/yr. Wet deposition of selenium could be relatively bioavailable as selenite is the dominant form.

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 Chesapeake Bay range from 1.4 – 1.8 ng/m^3. Different deposition velocities were used to estimate dry deposition fluxes for the Great Lakes (0.1 cm/s, Sweet *et al*. 1998) and Chesapeake Bay (0.26 cm/s low, 0.72 cm/s high; USEPA 1996). Selenium in the air is generally 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 6.1 – 127.5 kg/yr. Considering the fact that the largest single source of airborne selenium in the US is combustion of coal, the atmospheric deposition of selenium in the Bay area is likely to be at the lower end of the estimated range. The total load for both wet and dry deposition is estimated at less than 30 kg/yr.

5.2 Erosion and Transformations in Bottom Sediments

The majority of suspended sediment selenium enters the North Bay through the Delta and is exchanged with the bottom sediments, through continuous deposition and resuspension processes that vary in time and space. Overall, as explained below, the net selenium load due to deposition/erosion of bottom sediments is small, and dominated by riverine fluxes, which are subsequently lost due to discharge through the Golden Gate.

This selenium exchange between bottom sediments and water column represents ambient conditions and high proportion of elemental selenium in bottom sediments drastically limits its contribution to bioaccumulation. Therefore, release of selenium from bottom sediments is not considered as a source in the TMDL computations.

Selenium in bottom sediments in the North Bay, unlike suspended particulate selenium in general, is primarily in the minimally bioavailable elemental form, and their total concentration is about half the level reported elsewhere in freshwater, salt marsh, and estuarine sediments (Meseck and Cutter, 2012). Conditions such as pH, oxidation-reduction potential or the presence of metal oxides are among the key factors affecting the partitioning of selenium in the aquatic environment and controlling selenium transformations at the water column/sediment interface (USDHHS 2003). In the North Bay bottom sediments, average selenium concentrations in samples from the depth of 5 to 15 cm range between 0.16 – 0.41 µg/g, with a mean of 0.27 µg/g in the Bay stations (Meseck and Cutter 2012; reported as 2.04-5.25 nM/g) and the mean sediment concentration based on the RMP data is 0.25 µg/g. These levels of selenium are at the lower range of the concentrations measured in 66 marine sediments from the northwest Pacific Ocean, which ranged from 0.1 to 1.7 µg/g with a mean of 0.63 µg/g (Ihnat 1989). Recent RMP coring data show that, unlike some other contaminants in the Bay sediments (e.g. Hg, Cu, PCBs), selenium concentrations stay relatively constant with depth and have remained unchanged for decades (Yee *et al.* 2010). Selenium in the bottom sediments is dominated by elemental selenium, which is considered insoluble, less mobile than other forms of selenium, and much less bioavailable. For example, Doblin and others (2006) and Meseck and Cutter (2012) reported the proportion of elemental selenium in the Bay-Delta sediments greater than 50 percent. Selenium in bottom sediments can be mobilized to the water column through resuspension, erosion, diffusion and bioturbation or discharged through the Golden Gate to the ocean.

Quantification of selenium erosion is complex and may be approximated with modeling. Sediment transport was part of the ECoS3 modeling framework used to represent selenium transformations through the estuary (Tetra Tech 2010). The modeling suggested that the upper part of the estuary was erosional, consistent with the USGS estimates (USGS 2001a, b). However, the modeling also showed that the net selenium load due to deposition/erosion of bottom sediments was small compared to other sources (<20 kg/year) and subject to uncertainty because of its small net magnitude. The modeled exchange with bed sediments demonstrated that for different years the contribution of particular selenium can vary from -4 kg/yr to 10 kg/yr, with the highest contribution estimated during a wet year (2006), which coincided with the highest removal rates through the Golden Gate. As a modeling example, it was illustrated, by shutting off the bed sediment exchange completely, that the contribution to water column particulate selenium from the bed sediments was minimal. Also, the lack of a strong vertical gradient in the sediment cores, and the absence of a significantly elevated selenium source in deeper sediment layers, indicate that the bottom sediment supply will not change substantially even as certain areas of the Bay continue to erode. These supporting analyses suggest that although sediment resuspension is a contributor to water column particulate selenium, its overall effect, given other selenium sources, is limited and unlikely to grow with time.

Integration of the modeling with the sediment core speciation data, with a large fraction of elemental selenium and low concentrations overall, suggests that selenium from bottom sediments has a very limited or no net contribution to bioaccumulation.

6 LINKAGE ANALYSIS – RELATIONSHIP BETWEEN SOURCES, TARGETS AND BENEFICIAL USES

In order to determine the linkages between selenium sources and the TMDL targets, and to evaluate assimilative capacity of the North Bay, it is critical to understand the factors and conditions leading to selenium bioaccumulation in fish.

Selenium bioaccumulation is site-specific and driven by feeding habits of fish, and differences in choice of prey. Particulate selenium and dietary uptake is the most important exposure pathway for aquatic organisms, especially predators, and some types of food webs bioaccumulate selenium more efficiently than others. A conceptual representation emphasizing key factors affecting selenium transfer in two common food web types, benthic bivalve-based and pelagic crustacean-based in San Francisco Bay is shown in Figure 32.

In the North Bay, adverse impacts of selenium bioaccumulation have been detected only in the benthic food web, and are particularly evident where the invasive clam *Corbula amurensis* dominates. A significantly slower loss rate for selenium exhibited by *C. amurensis* as compared to native clams and crustaceans, results in high tissue concentrations (9.9±3.3 µg Se/g-dw , mean±sd, n=498 for 2000-10). This, in turn, poses a risk to the predators feeding on these clams, mainly white sturgeon.

6.1 Importance of Particulate Selenium in Managing Ecological Exposure

Although dissolved selenium dominates in the water column, the relatively small fraction (0.8-21.5 percent, mean: 10.3 percent) that is particulate is far more available to bivalves and zooplankton, and is therefore of special significance to bioaccumulation observed in the North Bay. Particulate selenium in the Bay water column is linked to the presence of total suspended material that comprises mineral and organic particles and exhibits significant temporal and spatial variability. Particulate selenium concentrations typically range from 0.2 to 1 µg/g (0.53±0.28; mean±sd, n=126). The most recent data (2010-12) indicate a decrease in particulate concentrations (0.45±0.25 µg/g, n=84) compared with observations from 1999 (0.69±0.30 µg/g, n=42; see Figure 6 in Chapter 3.3).

The direct intake of selenium by bivalves and higher level predators from the dissolved phase is extremely limited and, in fact, the pathway for nearly all selenium transfer to higher trophic levels is dietary exposure through particulate material (Luoma and Rainbow 2008). Biodynamic modeling shows that uptake of dissolved selenium is responsible for less than 2 percent of selenium found in tissue of bivalves (Presser *et al.* 2008) and even less in fish

(<0.16 percent for mangrove snapper). However, the aquatic cycling of selenium includes biotransformation of inorganic selenium to organoselenium by primary producers and microorganisms.

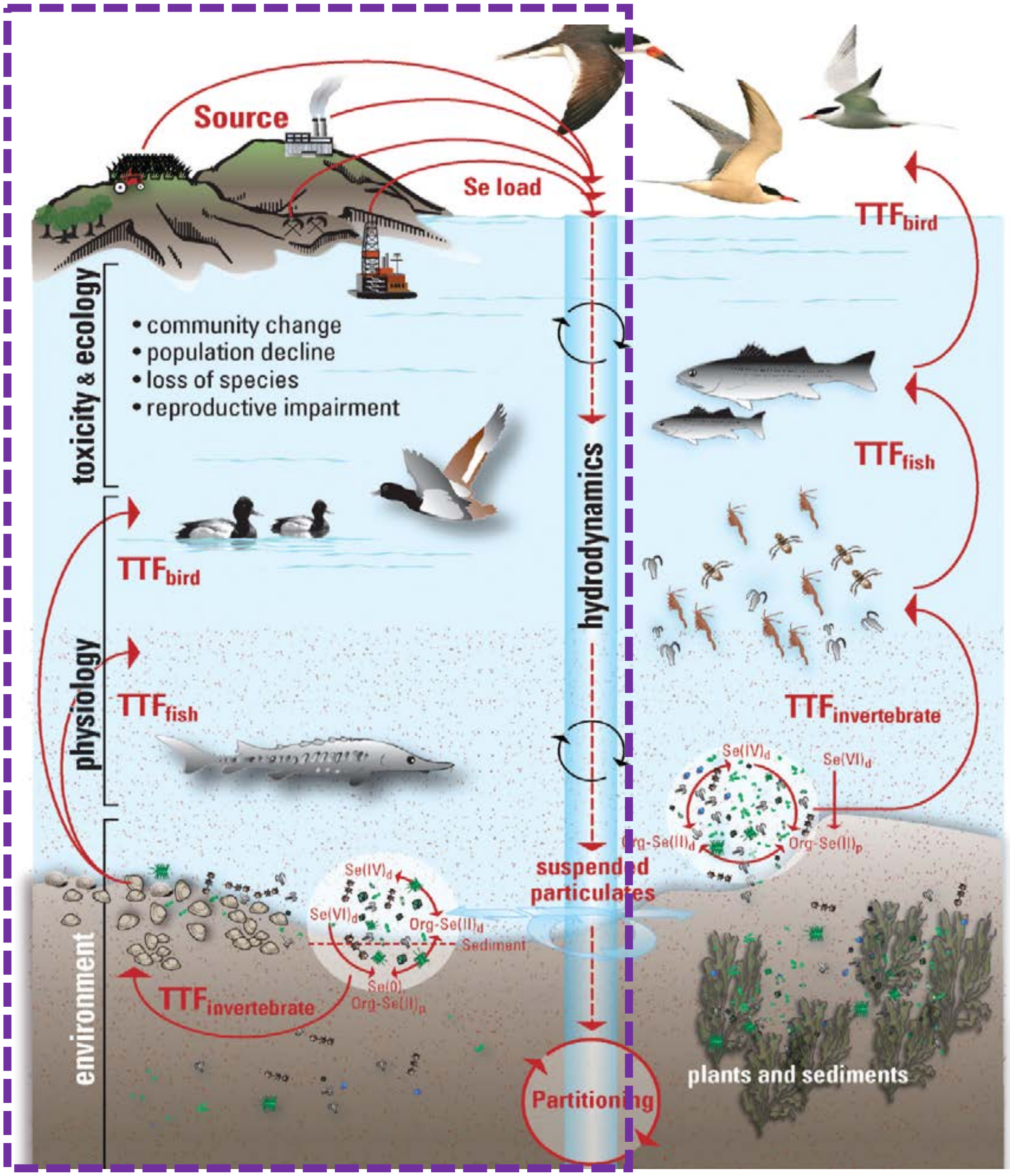


Figure 32: Conceptual model showing selenium biotransformations and implications for a benthic bivalve-based food web (*left panel*) and a water column food web (*right panel*)

(p - particulate, d-dissolved; from Luoma and Presser 2009)

Organisms such as phytoplankton, fungi and bacteria are able to take up and concentrate aqueous selenium and this uptake varies widely across species. Baines and Fisher (2001) demonstrated in laboratory experiments that marine algae cellular concentrations may exceed more than 100-fold ambient dissolved concentrations. These organisms will take up dissolved selenite and organo–selenide preferentially and rapidly convert it to organic selenides within their cells, thus becoming a rich source of particulate selenium to bivalves and other organisms that consume live and senescing algae. Uptake of selenate by algae is inhibited by sulfate content in the water column (N. Fisher, Stony Brook University. *pers. comm*); hence, since the sulfate concentration in sea water is several orders of magnitude higher than that of selenate, under conditions in the North Bay, uptake will be somewhat limited compared with the freshwater environment. Scientists now agree that the highest bioaccumulation takes place at the base of the food web (primary producers – algae, bacteria, fungi and plants) while the subsequent transfers to higher trophic levels, although biologically significant, tend to be much smaller (Chapman *et al.* 2009, Figure 33). In fact, comparison between concentrations in prey items and selenium levels in sturgeon implies that bioaccumulation in sturgeon occurs in an asymptotic fashion, and does not increase after sturgeon reach maturity.

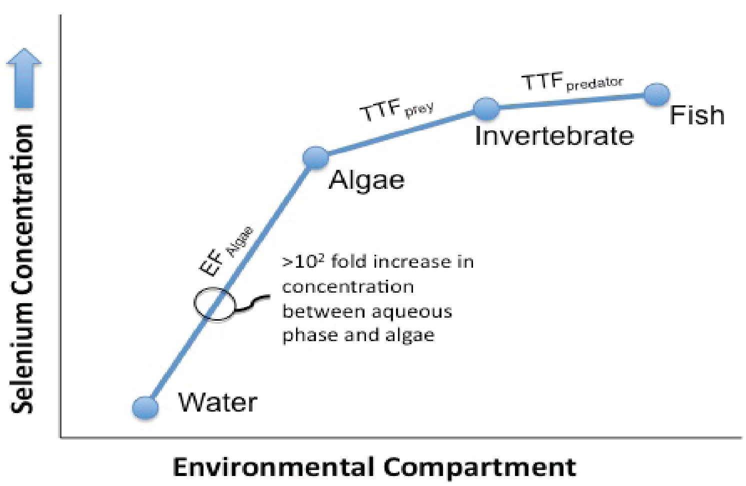


Figure 33: Selenium enrichment and trophic transfer in aquatic food web

(Chapman et al. 2009 - SETAC Pellston Workshop)

Particulate selenium in the estuary originates mainly from riverine inputs, with a smaller proportion of selenium coming from in-situ transformations. Riverine inputs of particulate selenium can be a significant source of selenium to the North Bay as large amounts of sediments and living and non-living particulate organic material enter the Delta from Sacramento and San Joaquin watersheds. Particulate river load was estimated to range from 170 to 1660 kg per year (see Chapter 5 for discussion of selenium sources and loads). In riverine inputs, particulate selenium is mainly present as particulate elemental selenium, adsorbed selenite and selenate and particulate organic selenide.

6.2 Modeling Framework

We explored the available mathematical and empirical models to help identify conditions that could potentially exacerbate selenium associated risks and explain processes that affect relationships between environmental and anthropogenic loads of selenium in the North Bay and bioaccumulation in biota. Figure 34 shows a modeling framework comprising a numerical estuary model and a bioaccumulation DYMBAM model selected to simulate transformations and biological uptake processes in the North Bay (Chen *et al*. 2012, Tetra Tech 2008c, 2008d).

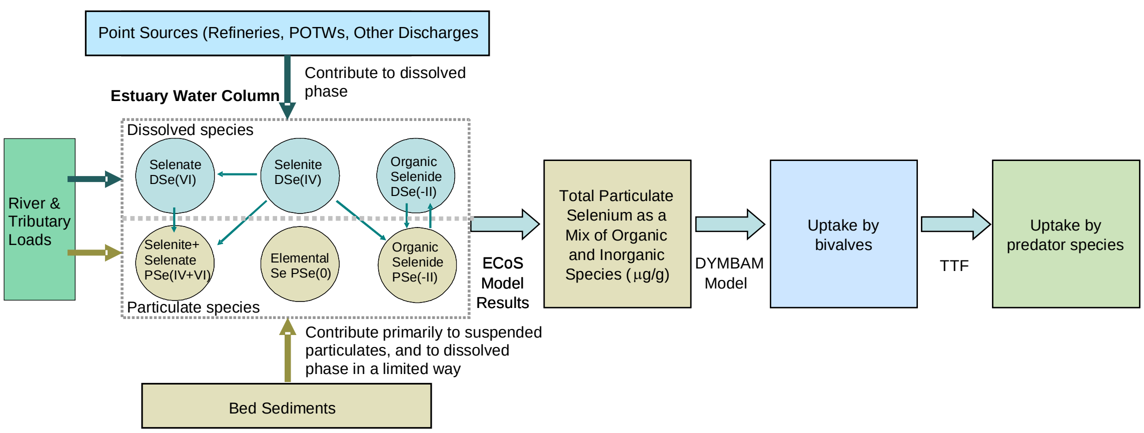


Figure 34: Schematic representation of the modeling framework linking selenium in water column and suspended particulates to bivalves, and then to predator species

The estuary model was developed using the ECoS3 framework and built upon the previous work of Meseck and Cutter (2006). The model was applied in a one-dimensional form with a daily time step. The estuary model simulates the biogeochemistry of selenium, including transformations among different species of dissolved and particulate selenium, salinity, total suspended matter (TSM), phytoplankton and water column concentrations, and the subsequent bioaccumulation of selenium in the North Bay. The aggregated output of the estuary model is subsequently used to evaluate selenium concentrations in bivalves and bioaccumulation of selenium through the food web by applying the empirical DYMBAM model (Presser and Luoma 2006) in a steady state mode.

The modeling framework, described only briefly in this report, provides a means to integrate and synthesize the existing information and to evaluate adaptive approaches to manage ecological exposure to selenium. The models were run to demonstrate how selenium discharges and other inputs can be related to the release mechanisms, secondary sources, and exposure pathways. For details on model application, assumptions, calibration and testing see Technical Memorandum 6: *Application of ECoS3 for Simulation of selenium Fate and Transport in North San Francisco Bay* prepared by Tetra Tech (2010), Chen *et al.* 2012, and the updated discussion of model runs in Tetra Tech (2015).

ECoS3 Estuary Model

The estuarine modeling framework ECoS3 was originally developed by the Center for Coastal and Marine Sciences at the Plymouth Marine Laboratory, UK, and subsequently used to simulate biological productivity, total suspended material, salinity, nutrients, and trace metal behavior in a range of European estuaries. As described in Harris and Gorley (1998), the ECoS3 framework contains modules that simulate transport and dynamics of different dissolved and particulate constituents in an estuary and can be applied in a 1-D or 2-D form.

It was first applied to model selenium in the North Bay by Meseck and Cutter (2006). In that application, equations to simulate transport and transformations of different species of selenium were formulated and the North Bay was modeled as a 1-D well-mixed estuary divided into 33 segments. The model domain starts from the freshwater end member at the Sacramento River at Rio Vista (X = 0 m; head) and extends to the mouth of the estuary at the Golden Gate (total length = 101,000 m). The head of the estuary is modeled as a closed boundary with seawater as an open boundary. The same spatial representation was also used in this project (Figure 35).

Salinity – Along the estuary gradient, salinity is governed by freshwater inflows, wind and tides, and simulated using advection and dispersion equations. During the high flow season, freshwater advection dominates and lower salinity is observed through the estuary. During low flow, salinity in the estuary increases as a result of reduced freshwater inflows. Water velocities are computed with cross section areas derived from the Uncles and Peterson model (Tetra Tech 2010).

Sediment Transport – Potential sources of sediments to the Bay include the Delta input, local tributaries, in situ resuspension and erosion, and in situ production due to phytoplankton growth. In ECoS3, total suspended material (TSM) is represented as three different components: permanently suspended particles (PSP), bed exchangeable particles (BEPS) and phytoplankton (B).

PSP is defined as suspended material that does not sink and does not interact with the bottom sediments, and is modeled in a manner analogous to a dissolved solute (Harris and Gorley 1998; Meseck 2002). BEPS originates from sediment resuspension. A small portion of BEPS also originates from the riverine input. BEPS is modeled as a function of sediment resuspension and deposition, as well as advection and dispersion. The dispersion of BEPS is proportional to mixing that occurs due to both freshwater inflows and tides.

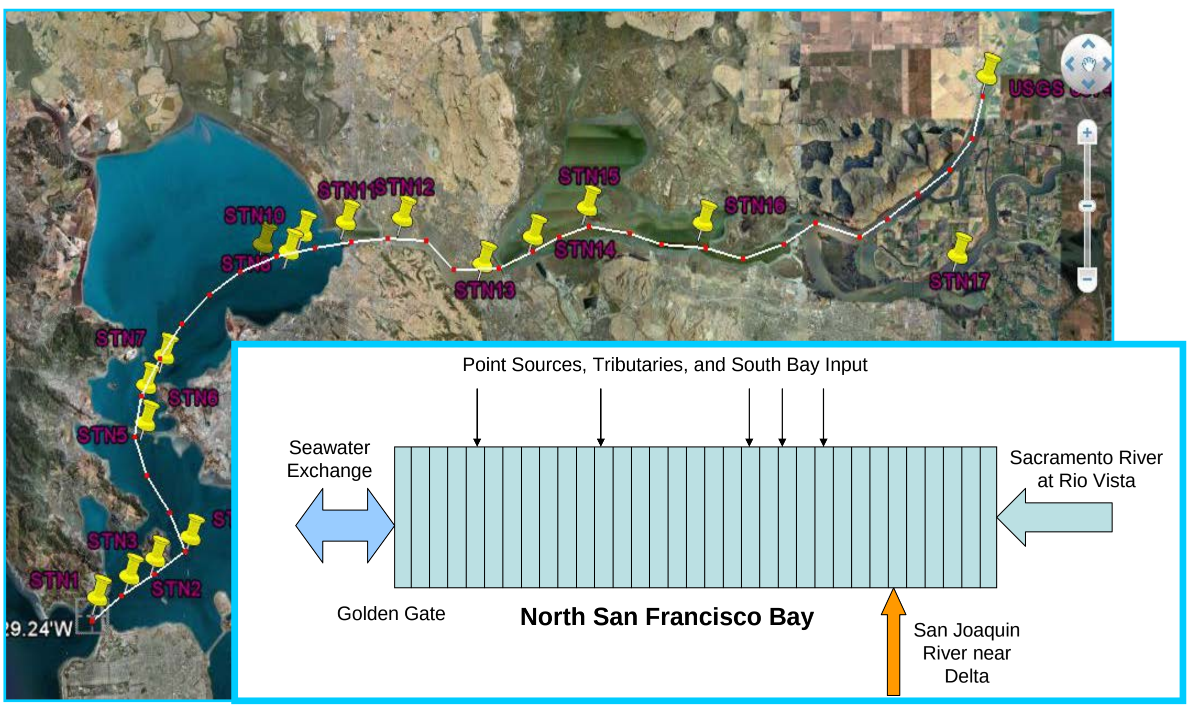


Figure 35: Spatial location of 33 model segments (*red dots*) **and schematic representation of the estuary showing boundary conditions and point source inputs**

Phytoplankton – The dynamics of phytoplankton play a key role in regulating selenium transformations. Dissolved selenium can be taken up by phytoplankton to form particulate organic selenium, which is bioavailable to higher trophic level organisms (Luoma *et al.* 1992). Phytoplankton is particularly affected by transport, growth and grazing by zooplankton and benthic organisms as well as settling and respiration (Meseck 2002) and modeled as a function of different sources and sinks. Benthic grazing can be a controlling factor in phytoplankton biomass. In laboratory experiments grazing rates observed for *C. amurensis* were found to exceed the specific growth rate of phytoplankton. Evident decreases in chlorophyll *a* concentrations observed in the Bay until recently, have been commonly linked to the invasion of *C. amurensis*. For further discussion of grazing effects and other limiting factors see Chapter 2 in Technical Memorandum 6 (Tetra Tech 2010).

Dissolved selenium – enters the North Bay from the Delta, local tributaries, refineries, municipal and industrial wastewater discharges, and in small proportion diffusion from sediment. Speciation of selenium from these sources is generally dominated by selenate (Se^{6+}), followed by organic selenide (Se^{2-}) and selenite (Se^{4+}). In the water column, these different species of selenium can undergo biological and chemical transformations.

Transformations of dissolved selenite include oxidation to selenate, uptake by phytoplankton and adsorption and desorption from minerals. Transformations of dissolved organic selenide include oxidation to selenite and uptake by phytoplankton. Dissolved organic selenide is also generated through mineralization of particulate organic selenide. For selenate, the transformation includes uptake by phytoplankton and microbes. Oxidation of selenite to selenate was found to be a slow process which can take hundreds of years, while oxidation of organic selenide to selenite occurs over a timeframe of weeks (Cutter 1992). Similarly, phytoplankton uptake of dissolved selenite and organic selenide was found to occur relatively rapidly (Riedel *et al.* 1996; Baines *et al.* 2004). Transformations between species are simulated as first-order kinetic reactions. Uptake and transformation processes of dissolved selenium are shown schematically in Figure 36.

Particulate selenium – can originate from riverine input, sediment resuspension, and in-situ production (e.g., phytoplankton uptake of selenium). Different species of particulate selenium are assumed to be associated with PSP and BEPS. Phytoplankton selenium is assumed to be present only as organic selenide. Riverine inputs of particulate selenium are specified as selenium content on riverine loads of particulates (PSP, BEPS, and phytoplankton). Although phytoplankton can be measured as part of the TSM, for this project phytoplankton and phytoplankton-associated particulate organic selenium are modeled separately. Particulate organic selenium associated with PSP is assumed to be selenium associated with organic carbon other than living phytoplankton (e.g., detritus of phytoplankton, plant material, and bacteria).

In the model, selenium content on riverine PSP is determined with calibrated parameters that are bounded by values reported in Doblin *et al*. (2006) and discussed in Chen *et al.* (2012) and Tetra Tech (2015). Particulate selenium associated with BEPS is subjected to exchange with particulate selenium in bed sediments at the same rates as sediment resuspension and deposition. Seawater end member concentrations of particulate selenium are specified as constants (as selenium concentrations of PSP in seawater) for an open boundary. The transfer from dissolved selenium to particulate selenium includes mineral adsorption (mostly for selenite) and phytoplankton uptake of dissolved selenium for all three dissolved selenium species.

Selenium in sediments is modeled as a combination of initial concentrations modified by resuspension and deposition through sediment-water interaction, as well as some riverine input. Due to the balanced resuspension and deposition rates of sediment, the changes in selenium concentrations in bottom sediments are small.

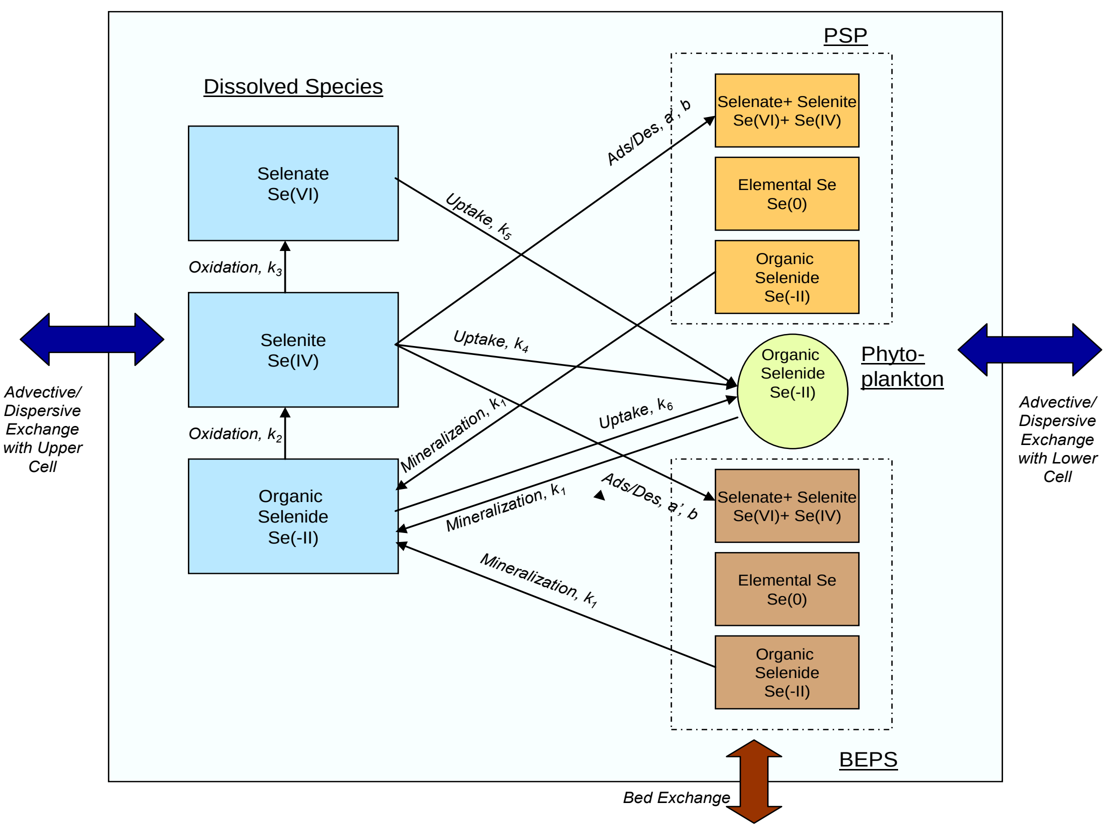


Figure 36: Interactions and transformations of dissolved and particulate selenium between different compartments in each cell of the ECoS3 model

DYMBAM Bioaccumulation Model

A dynamic multi-pathway bioaccumulation model (DYMBAM) describes contaminant accumulation and loss as a function of energy requirement in the lower trophic level organisms. DYMBAM uses species-specific empirically developed physiological rate parameters and environmental data representative of system conditions to assess and compare risks from metal exposure. In a steady-state application contaminant concentrations are expressed as a sum of waterborne and dietary uptake routes (Presser and Luoma 2006):

$$C_{ss} = \underbrace{\frac{k_u * C_w}{k_e}}_{\substack{\text{Water} \\ (\textit{dissolved})}} + \underbrace{\frac{AE * IR * C_p}{k_e}}_{\substack{\text{Food} \\ (\textit{particulate})}}$$

Where:

C_{ss} - steady state tissue Se concentration in clams
k_u - rate constant of Se uptake from water
C_w - Se concentration in water
AE - Se assimilation efficiency
IR - food ingestion rate
C_p- Se concentration in particulate material
k_e - the rate constant of loss

DYMBAM has been tested to be especially effective in determining selenium bioaccumulation in bivalves, copepods and polychaetes, and sufficient data exist to support assessments for benthic-based food webs with *C. amurensis* in San Francisco Bay. Applications of DYMBAM provide good compatibility with field observations despite simplifying assumptions and limited representation of bioenergetic responses in the model (Stewart *et al.* 2004). Model parameters to simulate selenium uptake by bivalves under a range of conditions are shown in Table 21. The ECoS3 model is used to determine concentrations of particulate selenium (organic selenide, selenite and selenate, and elemental selenium) available on a daily basis. Then the species composition in the daily food intake by bivalves is assumed to be the same as simulated by the ECoS3 model, and used to compute average selenium concentrations in bivalve tissue according to the equation above.

Table 21: Parameters for DYMBAM model

	Assimilation Efficiency (%) for Particulate selenium		
Ingestion Rates	elemental selenium	adsorbed selenite and selenate	organic selenide
0.45	0.2	0.45	0.8
0.25	0.2	0.45	0.8
0.45	0.2	0.45	0.54
0.85	0.2	0.45	0.80

Model Calibration and Evaluation

The basic predicted variables of the model (salinity, total suspended material, phytoplankton and dissolved and particulate selenium species) were calibrated using USGS data from 19 monitoring locations in the North Bay (http://sfbay.wr.usgs.gov/access/wqdata/) and from targeted selenium sampling across the estuary (Tetra Tech 2010). The main calibration periods for these parameters are from January 1999 to December 1999. Water year 1999 was selected for calibration of the model because of the availability of speciation data sampled during low and high flow periods. One-day time step was used in model runs, and the warm-up time was set to approximately 180 days starting from June 1, 1998.

The model calibration was done with a least squares minimization approach, using a fitting program provided by Dr. John Harris, the developer of the ECoS3 code. For every iteration, the sum of square deviation between observed and simulated values was calculated by the program and the parameters were adjusted for the next iteration to minimize the sum of square errors. After calibration the model was run to simulate the conditions in the Bay and the simulation results were validated for two hydrologicaly distinct years 1986 and 2001. Running a model for the year preceding the calibration period (hindcast mode) is considered to provide a good insight into the capability of the model to simulate conditions different from the calibration period in terms of hydrology and selenium loading. The results of these runs were compared with the observed data and the model performance was evaluated with two measures: correlation coefficient, and goodness of fit.

After initial evaluation of the model formulation and performance against the existing data, a series of model runs were conducted to gain more confidence in the model's ability to simulate selenium transformations across a range of conditions. The model was run under different input conditions and with different parameter values to assess the impact to selenium species concentrations. These tests offer better understanding of the functioning of the model by identifying processes and variables especially sensitive to the inputs, and point to the key variables where greater uncertainties may exist. The scope of the additional testing and the significance of each test are summarized in Table 22: .

In general, the testing of the calibrated model demonstrated the ability of ECoS3 modeling framework to represent the key characteristics relevant to selenium fate and transport in the North Bay. The model performs particularly well in simulation of physical features of the Bay such as salinity. Although poorer match was achieved between the observed and simulated results for suspended sediments and phytoplankton, numerous runs clearly have shown that the model is able to adequately simulate selenium in various compartments. For all the parameters modeled, the model is able to represent average conditions better than spatial and temporal peaks in concentrations. Also, longer-term evaluations capture phytoplankton transformations reasonably well.

The fact that peaks in flow and flow-controlled attributes cannot be fully captured is commonly observed in many models used to simulate environmental conditions. The value of these models lies in their ability to link complex environmental processes and reproduce longer term trends. The ECoS3-based modeling framework gives consideration to speciation effects and simulates temporal and spatial variations in selenium concentrations that compare well with the available field observations. It also offers a means to predict changes in selenium uptake by phytoplankton and bivalves and evaluate the effect of different load scenarios for the TMDL. The initial model calibration was verified using additional selenium data collected across the estuary between 2010 and 2012 (Tetra Tech 2015).

Table 22: Testing performed to assess model performance

Testing Performed	Significance
Sensitivity analyses	The calibrated model parameters are perturbed from their base case values to assess whether specific dependent variables respond significantly. Future model development and/or data collection must be targeted at the most sensitive parameters.
Changing Chlorophyll a	The model calibration and evaluation shows that chlorophyll ***a*** concentrations were sometimes poorly fitted with the ECoS framework. Additional model runs were conducted with varied chlorophyll ***a*** concentrations to better understand the importance of chlorophyll ***a*** to the predicted values of particulate selenium.
Changing uptake rates of dissolved selenium species	The uptake rates for selenate, selenite, and dissolved organic selenide are based on literature reports and calibrated to fit the data. Testing was performed to explore the impact of varying the rates over a wide range, from 10 to 100 times the rates in the base case calibration.
Different boundary conditions for riverine and seawater input	Particulate selenium concentrations in the riverine and seawater boundary have a significant impact on the concentrations in the Bay and the subsequent estimates of selenium levels in bivalves. Data to define these boundaries are scarce. Exploratory runs were performed over a wide range of values for both boundary conditions to evaluate simulated concentrations in the Bay.
Relative contribution of different sources of particulate selenium	Particulate selenium concentrations are the single most important constituent with respect to bivalve uptake, thus understanding of relative contributions from sources into the Bay: riverine, in-Bay sediment erosion or phytoplankton, and their effect on estuary concentrations is necessary for developing management options.
Spatial trends in particulate selenium	Spatial distribution of particulate selenium varies across the estuary. The model allows examining the main processes responsible for the small increases in particulate selenium observed towards higher salinities.
Mass balance	A mass balance of inputs and outputs provides a higher level check of the overall numerical representation. selenium sources, outflows, and changes in stored mass in the water column are presented.

6.3 Effects of Load Change

Point and Non-Point Load Change Scenarios

The calibrated and validated ECoS3 model, coupled with DYMBAM, was used to evaluate the effects of hypothetical changes in point and non-point loads on the dissolved and particulate selenium concentrations in water column and in bivalves in order to evaluate linkages to sources and to better understand the potential for system-wide transformations. Selenium loads were varied and compared to the existing conditions[7] simulated at different mid-estuary locations. The effects of changing the most prominent selenium sources: riverine (Sacramento and San Joaquin Rivers), San Joaquin River, and petroleum refineries are shown in Figure 37 (A, B) and discussed below.

For the simulated period of 1998-2012 the results show that the model is able to forecast changes in dissolved and particulate selenium, however, the response to load change is more pronounced in the dissolved phase. The increases in particulate selenium are much smaller under all scenarios tested. The shift between the simulated dissolved and particulate selenium concentrations results from the calibrated uptake and release rates that are based on the observed data.

When selenium load from refinery effluent was altered to demonstrate a hypothetical two-fold increase, the model shows that the dissolved selenium concentrations at Carquinez Strait would potentially increase by up to 30 percent, while particulate selenium would only increase by 4.5 percent. Likewise, when refinery load was removed completely, the particulate selenium concentrations would only decrease by approximately 3 percent (Tetra Tech 2015). The reduction of refinery loads by half would result in minor changes in dissolved and particulate selenium. Overall, at Carquinez Strait, the simulated contribution from refineries' load reduced by as much as 50 percent would result in decrease in selenium concentrations by only 0.018 µg/L (dissolved) and 0.016 µg/g (particulate). This leads to a conclusion that any further requirements to reduce loads from refineries will not contribute to a substantial decrease in particulate selenium levels. The load reductions achieved in the late 1990s and the change in speciation in effluent from more bioavailable selenite to less bioavailable dissolved selenium forms dominated by selenate have significantly lessened the impact of the refineries' discharge on water quality.

[7] Selenium concentrations and flows from all point and non-point sources are set at their best-estimate of historical values, i.e., selenium loads in the model are actual loads for 1998-2012 simulation period.

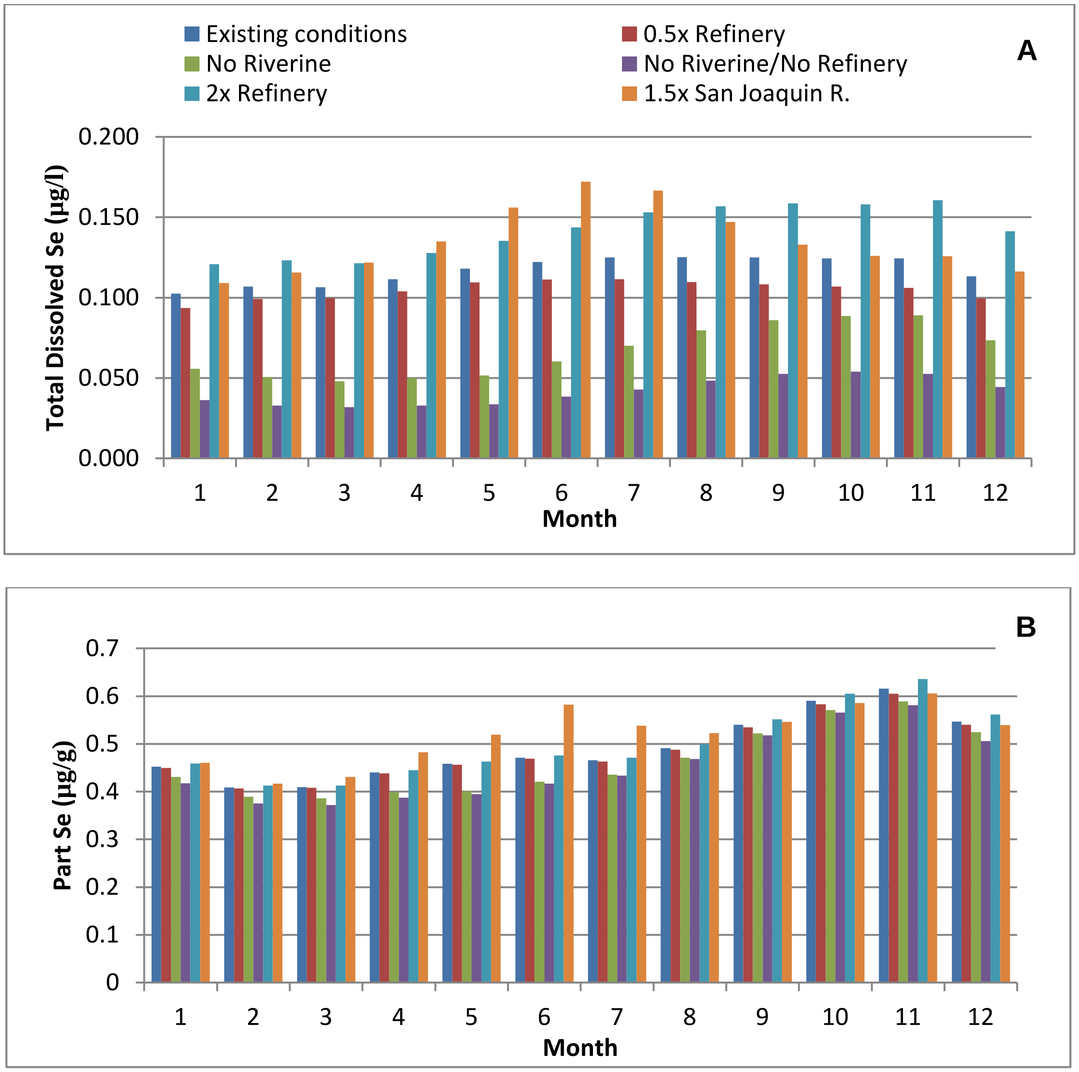


Figure 37: Predicted selenium concentrations for different loading scenarios

Under the existing conditions the impact of San Joaquin River is muted because most of its inflow is diverted from entering the Bay, and any variations in selenium loads are relatively small compared to the contribution of the Sacramento River (see Figures 3 and 4 in Tetra Tech 2014). However, if there is no continued reduction of San Joaquin River flow due to the State Water Project operations and other upstream diversions, the loads from San Joaquin River may increase. For example, a modeled 50 percent raise in the San Joaquin River flows, could cause the dissolved concentrations to increase by 0.038 to 0.05 µg/L during the summer months (May through July) (Figure 37 A), and the particulate selenium by 0.06 to 0.11 µg/g (Figure 37 B). Even factoring in these potential increases, the overall water column concentrations will remain below the TMDL target. The actions implemented through the Central Valley selenium TMDLs and restoration of agricultural lands to tidal systems are likely to contribute to continued reduction in selenium loading to the North Bay, however, monitoring of selenium concentrations and loads in San Joaquin River inflow is necessary to ensure that water quality in the North Bay is not impacted.

Background Conditions

The natural baseline concentrations in the North Bay are defined by selenium inflow from Sacramento River mixing with selenium from the ocean. The inflow from Sacramento River at the background level selenium concentrations (~0.07 µg dissolved Se/L) carries on average 4.3 kg Se per day or 3.1 to 5.5 kg/day during dry and wet seasons, respectively. The maximum daily load during high flows may be as high as 7 kg/day, while the average refinery load is relatively small and stable throughout the year at 1.5 kg/day.

A scenario was run to evaluate the effect of background conditions on selenium levels in the water column and *C. amurensis* (Tetra Tech 2015). This was defined as selenium loads that originate from natural background only, without significant anthropogenic influences (e.g., refinery discharges, agricultural drainage, and municipal and industrial discharges), and assuming conservatively the Sacramento River concentrations and speciation for the region including tributaries draining to the Bay. The San Joaquin River, which is known to have higher background selenium concentrations (0.2 – 0.5 µg/L) was assumed to have selenium levels at 0.2 µg/L and current speciation. On the other hand, in this scenario the impact of the San Joaquin River discharge remains somewhat diminished because the model run reflects current (1999 – 2012) flow conditions with only a small proportion of San Joaquin River flow reaching the Bay. Loads from petroleum refineries and municipal dischargers were set to zero.

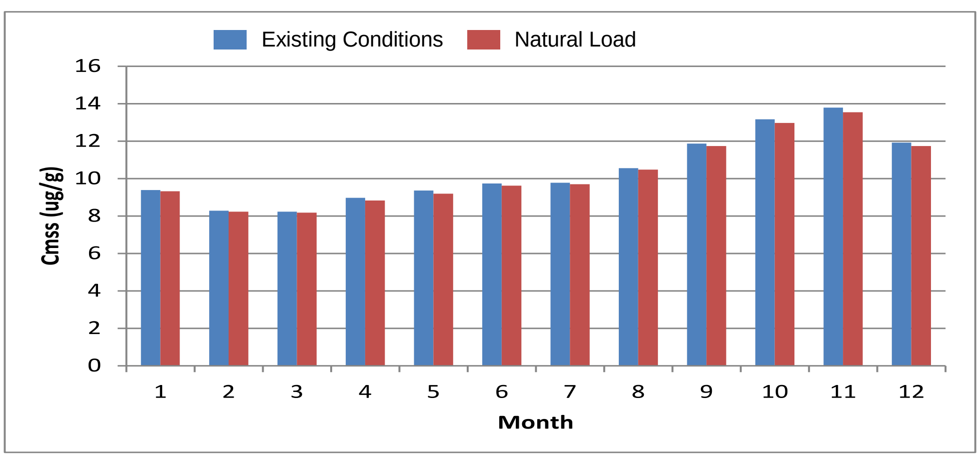
Depending on the location in the North Bay, the simulated background particulate selenium concentrations in dry season could vary from 0.557 to 0.841 µg/g (Table 23), and are only slightly lower than the modeled concentrations with refinery and municipal sources discharging to the Bay.

Table 23: Simulated particulate selenium concentrations for existing and natural load conditions

Location	Particulate selenium Concentration in µg/g [1]		
	Existing Conditions	Natural load	Change
Suisun Bay	0.563	0.557	0.006
Carquinez Strait	0.712	0.686	0.025
San Pablo Bay	0.872	0.841	0.031

[1] Simulated for an example dry season day (Oct. 30, 1999)

The results in Figure 38 show that, even under background load conditions, the concentrations of selenium in *C. amurensis* may reach highs similar to those currently seen in the North Bay, indicating that this invasive species plays a key role in amplifying available dietary selenium in the benthic food web. Much lower selenium concentrations are found in native clams due to low ingestion rates and higher loss rates. Higher selenium concentrations found in bivalves at the end of low flow/dry period may reflect the growth cycle of *C. amurensis*. For example, in San Pablo Bay they usually reproduce in spring and depend on phytoplankton blooms for food during spawning and growth, reaching their largest size in fall. Thus, selenium concentrations in the bivalve tissue may also result from the overall longer accumulation time (see section 6.4 for further discussion) and indicate cumulative impact of growth, diminishing freshwater flows, increasing residence times, and presence of particulate material.



Cmss (µg/g) – selenium concentration in bivalves

Figure 38: Model-predicted selenium concentrations in bivalves under natural background loads and with point source loads

6.4 Predicted Concentrations in Bivalves

Figure 39 shows predicted selenium concentrations in bivalves for an array of ingestion rates and assimilation efficiencies. The results are calculated using the DYMBAM model with the assumption that the composition of particulate selenium species in the daily input of food ingested by clams is the same as simulated by the ECoS3 model. The observed peaks in concentrations are influenced mainly by seawater/freshwater mixing and chlorophyll levels, which change from year to year and season to season. The clam feeding rates (biodynamic model parameters) are based on studies with *C. amurensis* in the laboratory, and represent the high end of the experimental values (Lee *et al.* 2006).

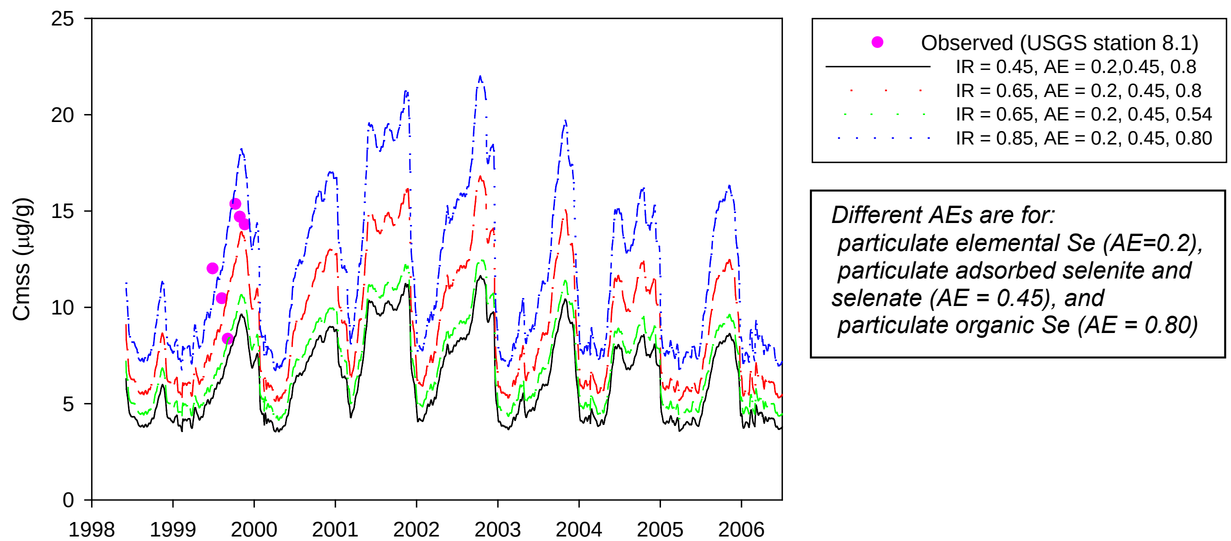


Figure 39: Selenium concentrations (Cmss) in *C. amurensis* simulated with different biodynamic parameters

The clam selenium concentrations were then modeled for the period prior to refinery load reductions (1995–1998) and following refinery load reductions (1999–2010) using measured riverine inflows, as well as the calibrated uptake rates and assimilation efficiencies for different selenium species based on the measured speciation data (Chen *et al.* 2012). Figure 40 shows the modeled concentrations in clams compared to the observed USGS data from Kleckner *et al*. (2010). From 1995 through 2010, the range of selenium concentrations in clams is between 5 and 20 µg/g and has not changed but there are notable declines in concentrations observed during the periods of elevated rainfall.

The model captures the long-term patterns in clam concentrations and explains the variability in the clam data collected from 1995-2010. Changes in clam selenium concentrations from the dry season to the wet season in each annual cycle could be explained by the riverine input of mineral selenium with lower concentrations and lower assimilation efficiency, which dominate during the wet season. Overall changes from year to year are influenced significantly by hydrology, with wet years (such as 2005 and 2006) resulting in lower clam concentrations. The ability to explain this temporal behavior provides insight into potential future changes in the Bay. Proposed flow increases in San Joaquin River to improve and restore fish populations may result in riverine inputs to the North Bay that differ from historical, both in volume and in the amount of particulate selenium. However, the simulation results suggest that these potential increases in dissolved and particulate selenium concentrations will be low, and the overall concentration in the North Bay will continue to stay well below the estimated allowable selenium concentration (the water column target of 0.5 µg/L) deemed protective of beneficial uses.

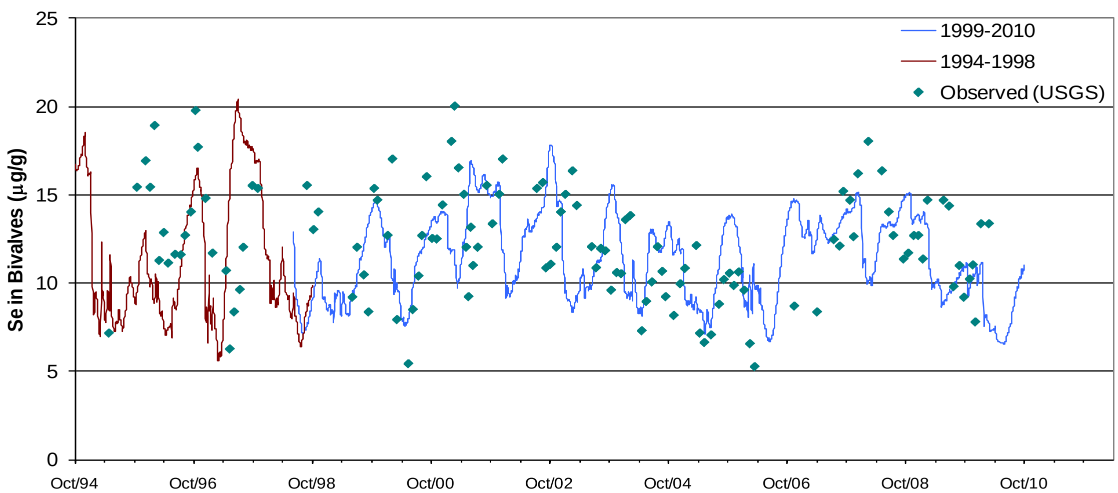


Figure 40: Simulated selenium concentrations in bivalve *C. amurensis* compared to long-term data from USGS at Carquinez Strait (1995-2010)

The levels of selenium in *C. amurensis* are likely to fluctuate and stay elevated compared to other benthic organisms. Not only do these clams exhibit a high propensity to bioaccumulate selenium based on their bioenergetic characteristics but they also appear not to differentiate between food sources of selenium, like other bivalves. For example, in laboratory experiments the Asiatic clam *C. fluminea*, more efficiently assimilates selenium associated with algae (66–87 percent) than selenium associated with oxic sediments (20–37 percent), however assimilation efficiencies from organic and sedimentary food types (19–60 percent) for *C. amurensis* did no show consistent difference (Lee *et al*, 2006). The modeling of clams under conditions which approximate natural background selenium levels in the North Bay also signals the ability of *C. amurensis* to reach concentrations in the 10 to 14 µg/g range. In addition, it appears that other factors such as rainfall and Delta flows that control salinity particularly in the North Bay, may alter conditions in which *C. amurensis* could thrive from year to year and thus affect selenium levels.

The clam tissue data were also independently evaluated by Stewart *et al*. (2013). Hydrodynamic modeling of refinery discharges as tracer releases indicated that elevated clam concentrations were likely to occur near refineries' outfalls, and that river inflows contributed to seasonal and annual variability in clam concentrations. However, the tracer modeling performed by Stewart *et al*. (2013) did not consider the presence of selenium from all other sources in the system. Moreover, the modeled high tracer concentrations are not directly related to the actual selenium concentrations at these locations. The authors concluded that point source refinery discharges and riverine inputs affected the clam selenium concentrations at different spatial and temporal scales. Selenium in clams was generally higher or lower depending on their proximity to the refinery discharges, and changed over time as river flows fluctuated.

While the true mechanisms of selenium uptake by clams are complex, and may only be partially explained through the modeling, the direct observations of clam tissue concentrations support the hypothesis that these concentrations vary over a wide range, and have not shown a clear shift in response to changes in refinery wastewater speciation and load reductions since 1999.

6.5 Assimilative Capacity

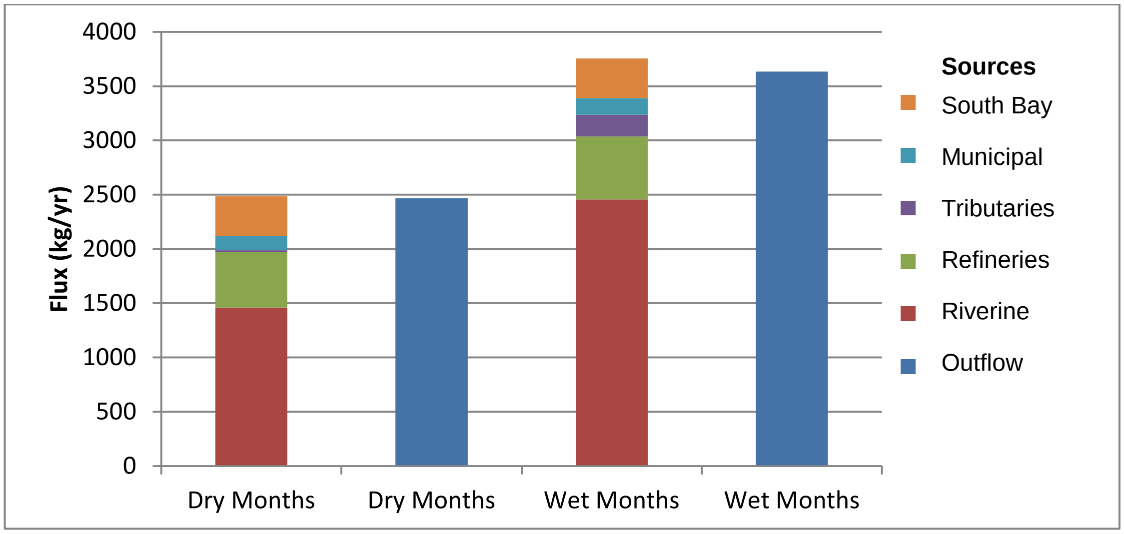
The link between selenium concentrations in fish and allowable dissolved and particulate concentrations in the water column, and modeling of selenium transformations originating from different sources, provide the basis for estimating the assimilative capacity in the North Bay.

Although comparisons of existing tissue selenium levels with the modeled thresholds may incorporate large uncertainties, there is large body of evidence to suggest that the North Bay could assimilate existing loads without adverse impacts.

First, the translation from the fish-tissue to water column concentration demonstrates that the TMDL targets could be attained and the beneficial uses protected when dissolved selenium concentration is below 0.5 µg/L. This concentration is up to 4 times higher than the ambient selenium levels in the North Bay (range: 0.053-0.147 µg/L, average 0.095 µg/L, n=97 in 2010-12). Furthermore, selenium concentrations have notably decreased since 1999 and are at low levels despite the inter-seasonal changes in flow and loading observed over the last decade (Figure 5).

Second, measured particulate concentrations in the North Bay for the 2010-2012 period range from 0.037 to 1.80 µg/g (n=84), with the 95th percentile of 0.85 µg/g, which is below the allowable concentrations derived from the ecosystem modeling approach. Allowable particulate concentrations can be back-calculated from the fish tissue target and presumed TTFs for fish and prey (Particulate = Fish-tissue target/(TTF_{prey}*TTF_{fish}). Even when the highest transfer efficiencies are considered for *C. amurensis* ($TTF_{C.\ amurensis}$ =17 => TTF_{prey}=*7.6*), the calculated allowable particulate concentration is 0.97 µg/g, which is higher than all but one sample from the North Bay. The ECoS3 modeling results also demonstrate that particulate concentrations, although variable, do not show a corresponding trend when large load increases are simulated (Tetra Tech 2014). The low sensitivity of the particulate selenium to shifts in dissolved selenium loading and hydrologic conditions results from the uptake and release rates in the ECoS3 model. These rates were calibrated using the observed dissolved and particulate selenium concentrations from the comprehensive transect data sets spanning more than a decade. Overall, the residence times and hydrologic conditions in the North Bay do not favor increases in particulate selenium, despite potentially notable increases in dissolved selenium. Based on the long term mass balance calculations, it appears that the extra loading of dissolved selenium is mostly transported out of the Bay before it is transformed into more biologically available forms (Figure 41).

Finally, the potential for selenium in the refinery discharge, the largest point source in the North Bay, to contribute to bioaccumulation was evaluated to verify whether it could affect water quality during dry seasons, when increasing residence time could amplify the impact of in-the-Bay selenium sources.



Wet = October through April; Dry = May through September
Outflow - loads exiting the Bay through Golden Gate

Figure 41: Annual fluxes of total selenium simulated for dry and wet months of 1998 - 2013

Effluent discharge from petroleum refineries comprises selenium in predominantly dissolved form with less than 2 percent being particulate selenium, which consists largely of elemental selenium, which is the least bioavailable of the different selenium forms. However, even dissolved selenium may be taken up by algae during residence in the Bay and become available in the particulate form. The proportion of particulate selenium that is traceable to the uptake of dissolved selenium by phytoplankton was estimated from a simplified steady-state model with selenium uptake and mineralization coefficients from the dynamic version of the ECoS3 model (Chen *et al.* 2012, Tetra Tech 2013). For typical dry-weather conditions with a 14-day residence time, changes in particulate phase were simulated at different locations in the North Bay, with and without inclusion of the refinery discharges. Bars in Figure 42 show background conditions at the eastern end of the estuary (1), increased particulate selenium concentrations due to phytoplankton growth at a downstream location (2), increased particulate selenium concentration due to dissolved uptake of selenium during the 14-day residence time 3), and the added component from the dissolved selenium uptake due to the dissolved selenium from the refinery effluent (4).

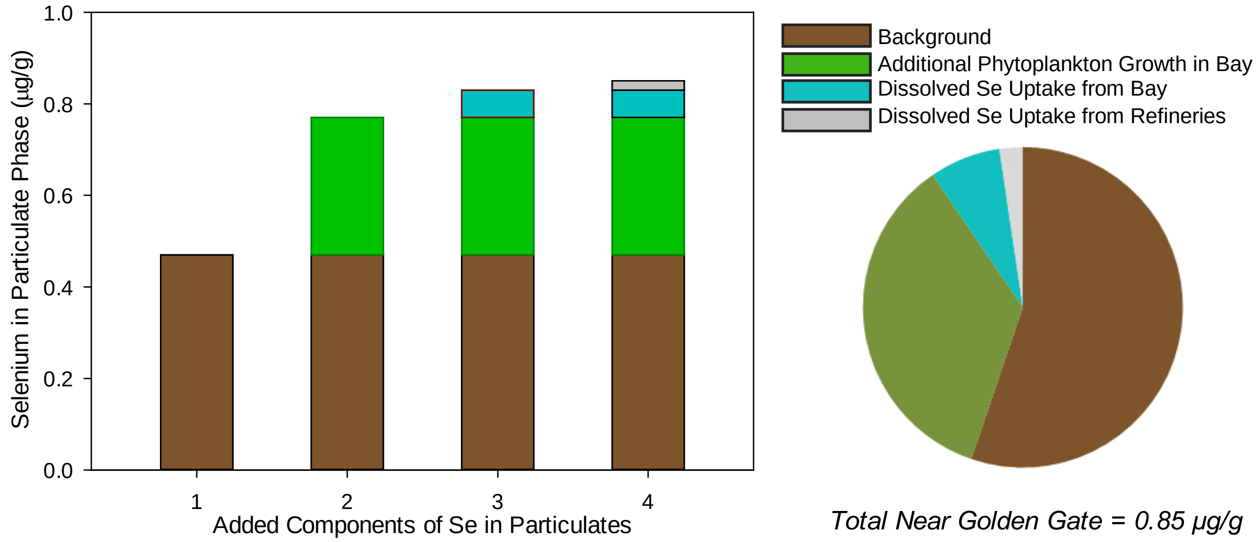


Figure 42: Simulated distribution and uptake of selenium by phytoplankton

For this hypothetical period, the concentrations in the particulate phase change from 0.47 µg/g at the eastern boundary to 0.85 µg/g near the Golden Gate. The increase is associated with greater phytoplankton abundance and with uptake of selenium by the phytoplankton during their residence in the Bay. The portion of the dissolved selenium that originates from refinery discharges is also taken up by the phytoplankton, and contributes 0.02 µg/g to the total particulate selenium, which accounts for approximately 5 percent of the total increase observed near the Golden Gate. Although the refinery effluent dissolved phase selenium loads are significant, these results show that, during the limited residence time in the Bay, their contribution to the particulate selenium is relatively minor. These results are in agreement with the selenium concentrations measured in the immediate vicinity of the refinery discharge points showing that, despite the large load from refineries, the particulate selenium concentrations are not much different than the surrounding transect station concentrations (Figure 43). The average receiving water concentrations near the outfalls are below the water column target of 0.5 µg/L and the dry season concentrations are usually lower than the wet season (Figure 44).

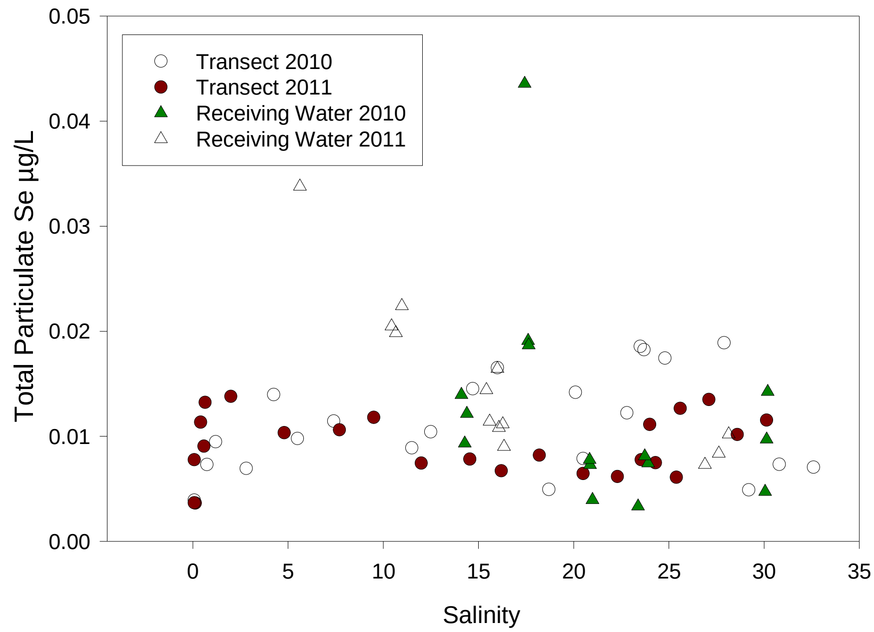


Figure 43: 2010-2011 dry weather total particulate selenium across the estuary and receiving water concentrations near the five refinery outfalls

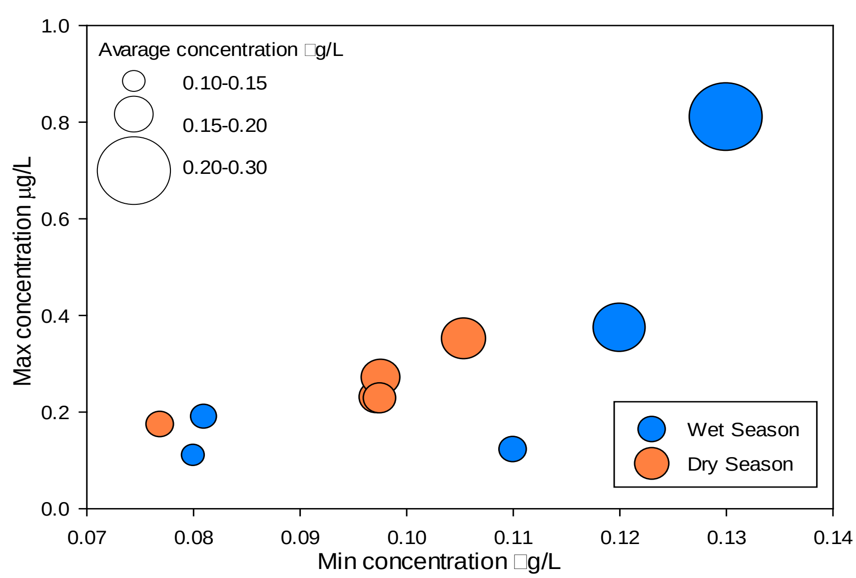


Figure 44: Minimum, maximum and average dissolved selenium concentrations during dry and wet seasons near refinery outfalls

Given that selenium concentrations in the North Bay are consistently low, and well below the background levels in San Joaquin River, the fact that the proportion of the more bioavailable selenite and organic selenium has not changed over the years, and limited uptake from dissolved and particulate phases during the residence in the North Bay, we conclude that current selenium loads do not exceed the assimilative capacity. By setting the TMDL to a conservative estimate of the existing load we can ensure protection of beneficial uses in the North Bay.

7 TMDL, LOAD ALLOCATIONS, AND MARGIN OF SAFETY

A TMDL is the total amount of a pollutant that can be assimilated by the receiving waterbody without exceeding applicable water quality standards. The TMDL for selenium in the North Bay is 5300 kg/year and represents the existing load to the Bay. Because of the long-term chronic effect of selenium on fish and its bioaccumulative properties as well as the strong seasonal variability in loads reaching the North Bay, the TMDL considers long-term estimates of loads from major nonpoint and point sources, and is expressed on an annual basis (Table 24).

Table 24: North Bay TMDL and load and wasteload allocations

Source Category		selenium Load	TMDL assumptions & calculations
Non-Point Sources	Central Valley Watershed	3300 kg/yr dissolved Se 770 kg/yr particulate Se **4070 kg Total Se/yr**	75th percentile of dissolved selenium load estimated with DSM2 and available concentration data for 1993-2012 at Rio Vista and Antioch. Average particulate selenium load estimated with annual suspended sediment load at Mallard Island (1995-2003) and particulate selenium data.
	Local Tributaries	**520 kg Total Se/yr**	Estimated with Method 1 which best describes average runoff conditions and takes into account all concentration data.
	Atmospheric Deposition	**Less than 30 kg Total Se/yr**	Wet and dry deposition
Load Allocations[1]			***4620 kg Total Se/yr***
Point Sources	Petroleum Refineries	**571 kg Total Se /yr**	Average annual load from 5 refineries estimated from the flow and concentration data for 2008-2012
	Municipal facilities Industrial sources	111 kg/yr 5 kg/yr **116 kg Total Se /yr**	Annual average load from 25 municipal facilities Annual average load from 2 industrial facilities
Wasteload Allocations			***687kg Total Se /yr***
Total TMDL			***5300 [2,3] kg Total Se/yr***

[1] Note that all non-point source loads (defined as load allocations) are strongly dependent upon hydrology, and can be expected to be higher or lower in wetter and drier years, respectively.

[2] Total TMDL load differs from column sum due to rounding

[3] Annual TMDL load translates to 14.5 kg Total Se per day

As discussed in Chapter 4.2, translation from the fish-tissue target demonstrates that the TMDL targets could be attained and the beneficial uses in the North Bay protected when dissolved selenium concentrations do not exceed 0.5 µg/L. This concentration is up to 4 times higher than ambient dissolved selenium levels in the North Bay (range: 0.06-0.13 µg/L n=77; average: 0.1 µg/L in 2010-12), which suggests an existing large assimilative capacity. However, uncertainties remain about the degree to which selenium affects fish, especially sturgeon in the North Bay. Therefore, we allocate only a fraction of the potential assimilative capacity which equals the conservatively estimated loads from all sources. The TMDL analyses indicate that in-Bay sediments are part of the natural background, do not change over time, and do not contribute to bioaccumulation on a quantifiable level. Therefore they are not considered as a source. Selenium allocations are assigned to sources based on the current loading contributions.

7.1 Wasteload Allocations

North Bay Petroleum Refineries

The wasteload allocations require petroleum refineries to discharge no more than their current combined load of 571 kg/yr. Table 25 lists individual wasteload allocations for petroleum refineries. These allocations were assigned based on each individual refinery's performance, and after considering each facility's concentration data and effluent volume for the period starting in 2000 through 2013.

Table 25: Proposed wasteload allocations for petroleum refineries

Permitted Entity	NPDES Permit	Allocation (kg/yr)
Chevron Products Company	CA0005134	111
Phillips66 *(formerly ConocoPhillips)*	CA0005053	93
Shell Oil Products US	CA0005789	244
Tesoro Refining and Marketing Company	CA0004961	60
Valero Refining Company	CA0005550	63
	Total	***571***

Municipal Wastewater and Small Industrial Dischargers

The proposed wasteload allocation requires municipal wastewater dischargers and two industrial facilities to discharge no more than their current combined load of 116 kg/yr.

Table 26 lists individual wasteload allocations for industrial and municipal wastewater treatment plants. These allocations were assigned based on each individual facility's performance, after considering each facility's effluent volumes and selenium concentration data which are low and on average well below the TMDL target. The discharge of selenium from individual facilities is small and has no measurable cumulative impact on the concentrations of selenium in the North Bay. The effluent is dominated by dissolved selenium (Table 27), and selenate, which is the least bioavailable species. The particulate selenium species constitute a small proportion of the effluent. Correlation of particulate selenium concentration with total suspended solids suggests that solids removal is generally effective at reducing the particulate fraction of selenium in effluent (Yee 2012). Overall, wastewater facilities perform well and show similar ability to remove selenium from their effluent regardless of treatment level. The likely cause of variability in the observed effluent concentrations between the facilities could be related to water supplies used for the service areas of individual plants.

Table 26: Proposed wasteload allocations for municipal and industrial discharges

Permitted Entity	NPDES Permit	Allocation (kg/yr)
City of American Canyon	CA0038768	1.6
City of Benicia	CA0038091	1.1
City of Calistoga	CA0037966	0.3
Central Contra Costa Sanitation District	CA0037648	17.4
Central Marin Sanitation Agency	CA0038628	4.0
Contra Costa Co. Sanitary District No.5	CA0037885	0.1
Delta Diablo Sanitary District	CA0038547	8.1
East Bay Municipal Utility District	CA0037702	30.0
Fairfield-Suisun Sewer District	CA0038024	9.7
Las Gallinas Valley Sanitary District	CA0037851	1.2
Marin County S.D. no 5	CA0037427	0.5
Mt. View Sanitary District	CA0037770	1.1
Napa Sanitation District	CA0037575	6.7
Novato Sanitary District	CA0037958	2.5
City of Petaluma	CA0037810	3.4
City of Pinole	CA0037796	2.2
Rodeo Sanitary District	CA0037826	0.4
Sausalito-Marin City Sanitary District	CA0038067	1.9

Permitted Entity	NPDES Permit	Allocation (kg/yr)
Sewerage Agency of Southern Marin	CA0037711	1.4
Sonoma Valley County Sanitary District	CA0037800	2.1
City of St. Helena	CA0038016	0.4
Treasure Island	CA0037810	0.1
Vallejo Sanitation & Flood Control District	CA0037699	6.7
West County Agency	CA0038539	7.9
Town of Yountville	CA0038121	0.2
Solvay (formerly Rhodia, Inc.)	CA0006165	0.5
USS-Posco Industries	CA0005002	4.5
Total		***116.0***

Selenium concentrations in effluents are generally within the range of ambient stream concentrations in areas where selenium is naturally occurring. The average total selenium concentration in the treated effluent is below the water column TMDL target of 0.5 µg/L dissolved selenium in 22 out of 25 municipal facilities. The remaining three facilities (City of American Canyon, Delta Diablo Sanitary District, and West County Agency) have average concentrations in the range of 0.6 to 0.75 µg/L based on the 2008-13 sampling period.

Table 27: Average percentages (±stdev) of dissolved and particulate selenium fraction in effluent from municipal facilities

North Bay municipal facilities	Dissolved selenium [%]	Particulate selenium [%]
Central Contra Costa Sanitation District	91 (±5)	7 (±4)
Delta Diablo Sanitation District	85 (±5)	9 (±3)
Fairfield-Suisun Sewer District	99 (±1)	2 (±1)
Vallejo Sanitation & Flood Control District	81 ((±4)	14 (±2)
All (7)[1] municipal facilities analyzed	89 (±8)	7 (±5)

From Yee (2012)
[1] Three additional facilities are located in the South Bay

However, the annual average concentrations for those facilities show significant decreases over the sampling period. For example, the concentrations measured in American Canyon effluent in 2008 averaged slightly above 1 µg/L, while average concentrations in 2012 and 2013 were 0.54 and 0.52 µg/L respectively. In addition, Delta Diablo participated in a special study to evaluate selenium speciation and fractionation in municipal wastewater effluent. This study showed that the speciation and concentrations in the Delta Diablo discharge were comparable to that of other facilities. As treatment technology in these three municipal facilities has not changed since 2008, the observed reduction in concentrations is likely due to refinement of the analytical methods[8] used to quantify effluent concentrations. Improvement in analytical methods resulting in lower detection limits and lower method interferences resulted in a 50 percent reduction of the estimated selenium effluent loads.

The average load discharged by a municipal facility is 4.4 kg/yr or 0.012 kg/day, and is less than 3 percent of the largely uncontrollable riverine inputs from the Central Valley watershed, and constitutes 2.2 percent of the TMDL assigned loading capacity. Among these facilities, 10 facilities discharge to local tributaries, 9 facilities discharge to San Pablo and Central Bays, and the remaining 8 facilities have outfalls in the proximity of Suisun Bay and Carquinez Strait. Low selenium concentrations in the effluent and relatively short residence times at the point of discharge suggest that selenium transformations, recycling and enrichment to more bioaccumulative forms are unlikely.

The potential for selenium from municipal facilities to cause or contribute to exceedances of selenium-related water quality objectives is low; therefore, water quality-based effluent limits are not recommended. Issuing and administering numeric effluent limits in the NPDES permits would incur costs but result in no substantial improvements in water quality in the North Bay. However, in order to manage selenium concentrations in their effluent at levels that do not contribute to selenium increases in receiving waters, these wastewater discharges need to continue solids removal consistent with Secondary Treatment Standards, which call for control of total suspended solids and biological oxygen demand. We also propose that any other facility with similar discharge characteristics to municipal facilities will be treated accordingly. To ensure that the performance-based allocations specified in this TMDL are being met, the dischargers will be required to document that their ongoing wastewater treatment is sufficient to prevent load increases.

7.2 Load Allocations

Table 24 lists load allocations for the Central Valley watershed (4070 kg total Se/yr), local tributaries draining into the North Bay (520 kg total Se/yr), and atmospheric deposition (<30 kg total Se/yr). Selenium loads from non-point sources undergo large seasonal and inter-

[8] Prior to 2008 number of dischargers contracted selenium analysis using USEPA Method 200.8 ICP/MS Collision cell mode that was later found to be positively biased. In 2008, the contract laboratory switched to USEPA Method 200.8 ICP/MS Reaction cell mode, which is equivalent to AA hydride research method employed by other laboratories.

annual variations. Therefore, proposed allocations are long-term estimates based on our understanding of hydrological conditions, spatial and temporal changes in rainfall and available data. These non-point sources are not controllable, and except for the San Joaquin River watershed, represent background conditions.

7.3 Margin of Safety and Seasonal Conditions

A margin of safety needs to be incorporated into the TMDL to account for uncertainty in understanding the relationship between pollutant discharges and water quality impacts. For the selenium TMDL, we are incorporating an implicit margin of safety by making conservative assumptions at each step of the analyses and calculations into the development of the numeric targets. The specific steps undertaken to ensure protectiveness of the TMDL are as follows:

1. The TMDL target is based on the USEPA draft criterion proposed for the direct reproductive effects in fish in freshwaters. These targets are more ecologically relevant and protective than the existing chronic National Toxics Rule objective (5 µg/L), which represents predominantly direct exposure to selenium in water. The draft USEPA criterion is more stringent than the effect levels observed in sturgeon, the fish of main concern in the North Bay. Additionally, in developing the draft chronic criterion, USEPA used effect concentration levels of EC10 rather than the traditional EC20, which lowered the estimated egg-ovary criterion from which the whole-body and muscle tissue concentrations were derived. Consequently, our TMDL target is conservative, is protective of sturgeon and all other fish species, and already incorporates an additional margin of safety by using a lower than normal effect level.
2. Environmental factors, such as hardness or salinity, have been used in the development of aquatic life criteria for toxic pollutants in recognition of their mitigating effects, and to account for the site-specific conditions in a particular water body. Studies indicate that fish seem to exhibit much higher resilience to selenium toxicity in saltwater with higher sulfate content than in freshwater, and that levels of sulfate occurring in the North Bay are likely to provide an additional level of protection against selenium toxicity.
3. Assumptions used in the translation of the TMDL fish-tissue target to water column concentrations followed recommendations in USEPA's freshwater criterion document, and employed conservative model parameter values in calculations of the allowable

dissolved selenium concentrations in the water column. Specifically, we used the 75th percentile for the K_d value. The K_d is the key factor controlling transformation efficiency between dissolved and particulate forms of selenium in the ecosystem-scale modeling, which ultimately determines concentrations in the food web. Although USEPA usually utilizes medians to characterize multiple measurements, by selecting the 75th percentile K_d in the translation we are reducing the range of modelled water column concentrations, which makes the translated water column target more conservative.

Seasonal variability in selenium loads was considered in the source analysis and load allocations. Long-term annual loads were estimated with data collected in wet and dry seasons to account for the seasonal changes in selenium transport and ratios of particulate and dissolved selenium present in the system. Selenium loads are strongly dependent on hydrology, and can be expected to be higher or lower in wetter or drier seasons or years. However, these seasonal impacts or other short term variability in loads are muted by the fact that selenium bioaccumulation in fish, especially sturgeon, is a long-term process and the differences in concentrations among individual fish are likely to be greater than seasonal variability.

8 IMPLEMENTATION PLAN

Because selenium water quality targets are currently being met, the overall intent of this non-degradation implementation plan is to ensure ongoing protection of the existing water quality and beneficial uses in the North Bay. Existing selenium concentrations in the water column are protective of aquatic life beneficial uses, and selenium sources in the local and Central Valley watersheds derive generally from naturally-occurring sources. The San Joaquin River watershed is an exception, due to agricultural sources in the watershed. TMDLs are already in place for this watershed and loads of selenium to the North Bay are expected to remain at current levels or less depending on changes in flow regime, which are currently under discussion. Therefore, no reductions of selenium loads or new implementation actions are required by this TMDL. The main goal of the implementation plan is to prevent increases of dissolved selenium concentrations and maintain safe levels of selenium in fish, specifically sturgeon. We propose to accomplish this goal through the following actions:

- Establish performance-based effluent limits for petroleum refineries;
- Continue control actions to reduce loads from the Central Valley watershed;
- Continue ambient water quality monitoring and require tracking of inflow from San Joaquin River; and
- Continue special studies to resolve nonlethal approaches to fish tissue sampling.

8.1 Internal and External Sources

Petroleum Refineries

Wasteload allocations for the five North Bay petroleum refineries will be implemented through NPDES permits. The annual average wasteload allocation established for each facility will be implemented as a performance-based mass limit expressed in kg/day. Compliance with the mass limits will be assessed on a monthly basis. The monthly average of daily loads should not exceed the mass limit. A monthly averaging period is consistent with the USEPA recommendation of a monthly attainment period for the water column element of the selenium chronic criterion[9].

Numeric effluent limits will be calculated as the 95th percentile of the daily loads and will be based on the length of data representative of each refinery performance during the period

[9] Selenium accumulation and depuration is considered sufficiently slow for the ambient 30-day averages to be protective of sensitive aquatic life stages.

from 2000 through 2012. We are proposing the 95th percentile to account for variability in refinery flows and selenium concentrations (e.g. as a result of different crude oil received and processed). Establishing mass limits as the 95th percentile of daily loads is consistent with the proposed annual wasteload allocations. Petroleum refineries should report their average annual load once per permit term.

Effluent Limit Calculation Approach

Since petroleum refineries measure paired effluent flow and selenium concentration approximately once per week, there is a large body of concentration data, more than 600 data points, from which to estimate daily loads. We calculated daily loads using the available daily flows and corresponding selenium concentrations for the period from 2000 through 2012. Our analysis indicates that the daily load data generally fit a log-normal distribution and that small deviations from normality can be attributed to upsets at the wastewater treatment facilities.

Table 28 illustrates the 95th percentile-based effluent limits. For this example, a small number of unusually high daily loads, indicative of treatment system malfunctioning, were excluded from each refinery's data set prior to calculating the limits. Final calculations of mass limits to establish numeric effluent limits will be performed at the next cycle of permit reissuance for each refinery. The calculations will exclude data when there has been a treatment system malfunction.

Table 28: Preliminary estimates of performance-based numeric effluent limits based on 95th percentile of daily loads (2000-2012)

Refinery	Chevron	Phillips66	Shell	Tesoro	Valero
Mass limit (kg/day)	0.68	0.47	1.14	0.42	0.34
Outlier exclusion threshold	Loads > 0.9kg	Loads > 0.54kg	Loads > 1.4kg	Loads > 0.45kg	Loads > 0.6kg

Performance-based numeric effluents limits will achieve the proposed wasteload allocations. Antibacksliding requirements will ensure that petroleum refinery selenium effluent limits do not increase. Petroleum refineries will continue to participate and support studies to evaluate potential impacts of selenium on water quality.

Municipal and Small Industrial Dischargers

As discussed in Section 7.1, the municipal and two small industrial dischargers are not required to have numeric effluent limits for selenium in their NPDES permits because they have an insignificant impact on North Bay water quality and do not require further controls or selenium reductions to ensure implementation of the TMDL. To help protect against degradation of the North Bay, these municipal wastewater and small industrial dischargers will be required on a periodic basis to document that ongoing wastewater treatment is sufficient to prevent load increases. Specifically, NPDES permits for these dischargers will be structured to require that once per permit term, the dischargers shall evaluate selenium loads over the previous permit term and verify that they are continuing to be equal to or less than the wasteload allocations identified in Table 26. The dischargers will conduct or case to be conducted monitoring and special studies to ensure the numeric targets and wasteload allocations are being attained.

Central Valley Watershed

The Sacramento and San Joaquin River watersheds are the largest source of selenium to the North Bay. These sources are mostly uncontrollable and related to selenium occurring naturally in soils and sediments. While concentrations of selenium in Sacramento River are the lowest in the region, the San Joaquin River concentrations are up to an order of magnitude higher. Soils on the west side of the San Joaquin Valley are derived from marine sedimentary deposits that are high in selenium and salts, and irrigation and drainage of these saline soils contributes selenium into the agricultural drainwater, much of which is eventually conveyed to the San Joaquin River and downstream to the Delta and North Bay.

The Central Valley Regional Water Quality Control Board (Central Valley Water Board) adopted three selenium TMDLs in the San Joaquin Valley, upstream of the town of Vernalis, to address selenium impairment in agricultural drainage and the San Joaquin River-watershed. The program that implements the Salt Slough, Grassland Marshes and San Joaquin River TMDLs was first adopted in the Regional Board's 1996 Basin Plan Amendment. The key component of the selenium management program is the Grasslands Bypass Project (GBP). It is a drainage control project designed to:

- Re-route high selenium subsurface drainage water via the San Luis Drain and a six-mile segment of Mud Slough into San Joaquin River to avoid wetlands;

- Implement best management practices on farmlands to reduce selenium loads and achieve selenium objectives in the mainstem of San Joaquin River below the confluence with the Merced River;
- Achieve short-term load reductions by October 2010;
- Bring Mud Slough and lower portion of San Joaquin River above the confluence with the Merced River to compliance by 2019; or
- Prohibit discharges not meeting water quality objectives.

Waste Discharge Requirements (WDRs) issued by the Central Valley Water Board specify the maximum monthly and annual average loads of selenium that the GBP may discharge into the San Joaquin River and other waterbodies. Selenium milestones and targets for the GBP are shown in Figure 45. The main mechanisms to control agricultural drainage include source control efforts such as selective land retirement, irrigation efficiency and channel lining to control seepage, drainage blending and re-use; and, to a limited extent, temporary discharges. Since the implementation of the project, these efforts have reduced the amount of discharge substantially resulting in an end to selenium discharge into wetlands and refuges. In addition, the load of selenium discharged from the Grassland drainage area was reduced by more than 90 percent (from over 10,000 lbs in 1996 to slightly over 1,000 lbs on average for 2010 through 2014).

Attainment of the load allocation established in this TMDL for the Central Valley watershed relies on continued efforts to manage and reduce discharge of agricultural subsurface drainage in the San Joaquin River watershed. Results to date demonstrate progress towards achieving the approved water quality targets by 2019. The reporting and monitoring requirements already imposed by the Central Valley Water Board will demonstrate compliance with the implementation goals of the TMDLs in the Central Valley watershed and this selenium TMDL for the North San Francisco Bay.

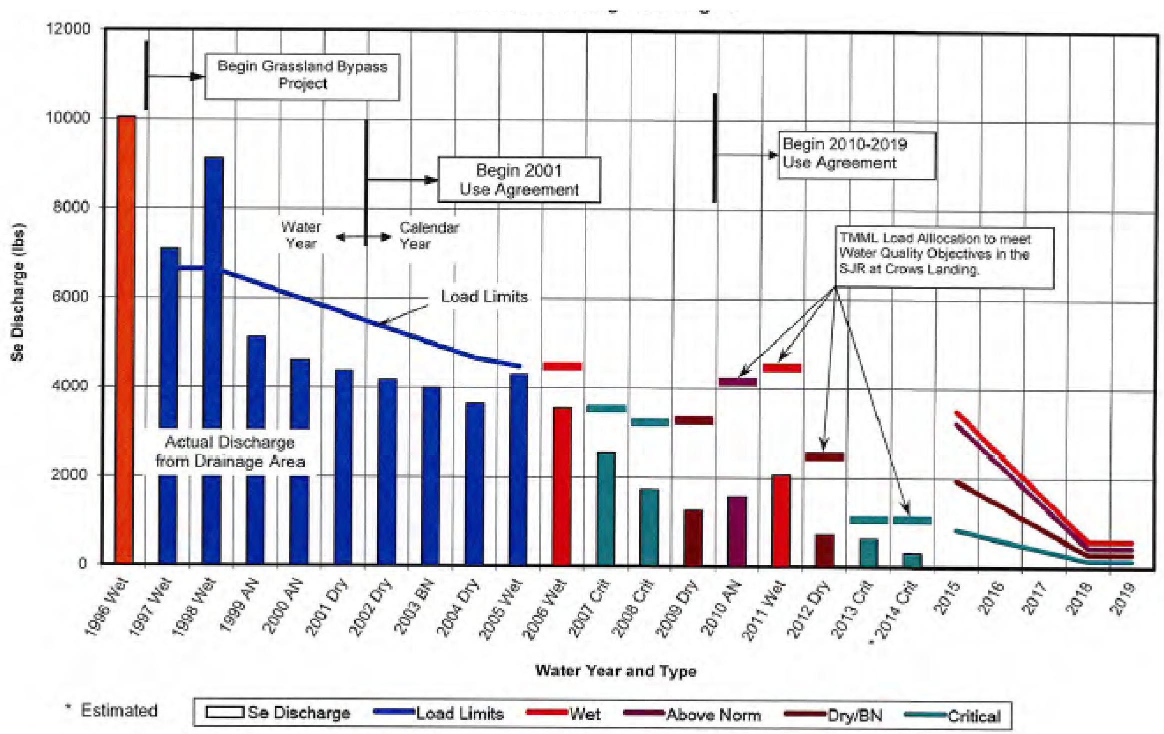


Figure 45: Selenium discharge and targets for the Grassland Drainage Area

Selenium loads from San Joaquin River to the North Bay may change if there are increases in the flow of San Joaquin River water to restore beneficial uses and maintain fish populations. This could result in larger volume of inflow to the Delta and the Bay. The current loads are partially reduced because of diversions of San Joaquin River water for domestic and agricultural uses prior to entering the San Francisco estuary. The State Water Board is considering updating the Bay-Delta Plan to establish new flow objectives and new salinity objectives for the lower San Joaquin River and the southern Delta. The proposed plan encourages an adaptive approach to allow for integration of new scientific information into development and implementation of new flow requirements as well as coordination among agencies responsible for ecosystem protection and water supply. We recommend establishing monitoring to track and evaluate selenium concentrations and loads entering the North Bay from the Central Valley watershed with a specific focus on the San Joaquin River. Monitoring is already ongoing or should be required as Delta outflow objectives are adopted by the State Water Board.

Local Tributaries

The local tributaries' allocation of 520 kg of total selenium per year includes urban and non-urban runoff. This source reflects concentrations of selenium reflective of natural background. The monitoring data and the conceptual understanding of selenium impacts do not indicate that urban runoff conveyances are contributing to the selenium impairment in a measurable way, and no implementation actions are required for this source.

Separate from this TMDL, requirements already exist under the provisions of the Small MS4 General Permit (Order no: 2013-0001-DWQ) and the Phase I Municipal Regional Stormwater Permit (MRP) (Order no: R2-2009-0074), for the continued implementation of urban runoff control measures for high priority pollutants other than selenium. It is anticipated that these actions will maintain selenium concentrations and loads at the existing levels, representative of background conditions.

MRP permittees are also monitoring water quality in tributaries to the Bay. Provision C.8.e of the MRP requires monitoring of pollutants of concern in local tributaries and runoff, which will provide a vehicle to track water quality in the streams draining into the North Bay.

Atmospheric Deposition

Atmospheric deposition of selenium in the North Bay results from natural processes and sources. This load is very low and represents background conditions. Therefore, no implementation actions are needed to address this source.

8.2 Relevant Monitoring and Special Studies

Monitoring is needed to demonstrate that selenium concentrations in fish and water column remain low and that the TMDL targets are attained. The discharger-funded San Francisco Bay Regional Monitoring Program (RMP) collects ambient water quality data and conducts special and pilot studies to support water quality management in the Bay. The Water Board will call on dischargers to support the RMP to continue monitor selenium at a spatial scale and frequency necessary to determine trends, and ensure that water quality and beneficial uses in the North Bay are protected.

The TMDL analysis is based on the uptake of selenium into white sturgeon, a long-lived fish, with a limited population in San Francisco Bay. Finding a means to obtain a larger number of white sturgeon muscle samples on a more frequent basis is necessary to assess selenium bioaccumulation, and to track inter-annual trends. In 2009, in addition to standard analyses in sturgeon fillets, tissue plugs were analyzed as a surrogate for sampling from a whole fish. This attempt to establish a nonlethal method was repeated in 2014 to obtain a larger sample size for more precise correlation of both types of samples. If plug sampling is found to be suitably accurate, it may form the standard methodology for future sample collection by the RMP and provide an opportunity to monitor sturgeon nonlethally, through collaboration with the California Department of Fish and Wildlife and other agencies.

No new requirements for conducting studies are recommended by this TMDL. Since the dischargers, through their participation in the RMP, are currently supporting efforts to evaluate nonlethal approach to sturgeon sampling, we expect the necessary studies to be completed voluntarily. In addition to testing the efficiency of plug sampling, in 2015 the RMP collected additional tissue samples including muscle, blood and eggs. Sampling of sturgeon eggs, although logistically more challenging, would provide a more direct metric of the risk to sturgeon reproduction and allow correlation between muscle/plugs concentrations and egg concentrations, which, in turn, could enhance the application of muscle plugs as an impairment indicator.

Samples of fin rays were also collected in 2015. Sampling of fin rays is an innovative technique that is non-harmful, easy to use by non-specialists, and, potentially, of lesser risk to the fish than muscle plugs. Fin rays have a regular growth pattern similar to growth rings of a tree and could be used to analyze selenium concentrations in each annular growth ring to assess life history of chemical exposure. Understanding selenium tissue concentrations in the North San Francisco Bay sturgeon over time will be important to help understand the dynamic of selenium bioaccumulation and evaluate whether or not changes in selenium water chemistry and prey from year to year could be related to changes in tissue concentrations in sturgeon.

As described in the discussion of the implementation of the Central Valley watershed allocations, the Water Board will work with the State Water Board to establish monitoring to confirm that selenium concentrations and loads in San Joaquin River inflow do not increase due to changes to the State Water Project operations, upstream water diversions, and San Joaquin River flow modifications.

Petroleum refineries and municipal and industrial wastewater dischargers will monitor their loads to demonstrate that they meet the wasteload allocations.

8.3 Adaptive Implementation

The selenium TMDL was developed using the best available information and scientific understanding of hydrology, and chemical and biological processes leading to bioaccumulation of selenium in fish and wildlife. However, uncertainty remains with respect to the complexity of a natural system as large as the San Francisco Bay Estuary relative to the most sophisticated conceptual and numeric simulation models. Adaptive management allows for implementation of this TMDL based on our current understanding, and we will continue to improve our knowledge of long-term responses to current and future loadings of selenium to the North Bay. Information from the ongoing monitoring programs, special studies, and modeling will help confirm whether selenium concentrations in the North Bay remain low, and do not exceed environmental thresholds. If monitoring of loads from the Central Valley watershed indicates increasing loads and nonattainment of the TMDL targets, we would work with the Central Valley Water Board regarding implementation of their existing TMDLs to control selenium discharges, and to identify additional management measures, if needed.

At a minimum, the Water Board staff will periodically evaluate water quality monitoring results and verify that TMDL targets and load allocations are met. We will also evaluate any new and relevant information from special studies and scientific literature including the outcomes of the USEPA's effort to update the existing selenium criteria for the San Francisco Bay.

9 REGULATORY ANALYSES

9.1 CEQA Analysis

This section presents the analyses required under CEQA when the Water Board adopts a Basin Plan amendment under the Water Board's certified regulatory program (Pub. Res. Code § 15251(g)). The Water Board is the Lead Agency responsible for evaluating the potential environmental impacts of Basin Plan amendments. Staff prepared the required environmental documents, which include an Environmental Checklist and a written report (this Staff Report) that disclose any potentially significant environmental impacts of the Basin Plan amendment. This Staff Report, including the CEQA checklist and analyses, constitute a substitute environmental document. To satisfy CEQA's recommendation to engage the public and interested stakeholders in consultation about the scope of the environmental analysis, a scoping meeting was held on April 3, 2015.

The State Water Board's regulations require a substitute environmental document to include 1) a brief project description; 2) an identification of any significant or potentially significant adverse impacts of the proposed project; 3) an analysis of reasonable alternatives to the project and mitigation measures to avoid or reduce any significant or potentially significant adverse environmental impacts; and 4) an analysis of the reasonably foreseeable methods of compliance (Cal. Code Regs., tit. 23, § 3777, subd. (b). Where there is no fair argument that the project could result in any reasonable foreseeable environmental impacts, the substitute environmental document need not contain an analysis of reasonably foreseeable alternatives. Similarly where there is no fair argument that the reasonably foreseeable methods of compliance with the project could result in any reasonably foreseeable significant adverse environmental impacts, the substitute environmental document need not contain an analyses of reasonably foreseeable alternative methods of compliance or mitigation measures. (Cal. Code Regs. tit. 23, § 3777, subd. (e) and (f).

9.2 Environmental Checklist

Project Title:	Proposed Basin Plan Amendment for Total Maximum Daily Load (TMDL) for Selenium in North San Francisco Bay
Lead Agency Name and Address:	California Regional Water Quality Control Board, San Francisco Bay Region 1515 Clay Street, Suite 1400 Oakland, California 94612
Contact Person and Phone Number:	Barbara Baginska (510) 622-2474
Project Location:	North San Francisco Bay, California
Project Sponsor's Name and Address:	California Regional Water Quality Control Board, San Francisco Bay Region 1515 Clay Street, Suite 1400 Oakland, California 94612
General Plan Designation:	Not Applicable
Zoning:	Not Applicable

1. Description of Project:

The project is a proposed Basin Plan Amendment for a TMDL and implementation plan for the North San Francisco Bay segments, including a portion of the Sacramento/San Joaquin Delta, Suisun Bay, Carquinez Strait, San Pablo Bay and Central Bay. The TMDL is based on attainment of a water column and fish tissue target concentrations protective of aquatic life and human health. Selenium concentrations in sturgeon have been gradually decreasing since the late 1990s with the majority of samples staying generally below the muscle tissue target of 11.8 µg/g. The concentrations in water column are consistently meeting the targets. The goals of the project are:

- Comply with the CWA requirement to adopt a TMDL for Section 303(d)-listed water bodies;
- Protect the overall aquatic health and human health beneficial uses of the North Bay and enhance its aesthetic and recreational values;
- Establish numeric targets protective of North Bay beneficial uses;
- Determine selenium loads protective of North Bay beneficial uses; and
- Establish an approach for implementation consistent with meeting the wasteload allocations to achieve the TMDL.

The project establishes a TMDL of 5300 kg Selenium/year, which is equal to the sum of current loads from major external sources. The project does not require load reductions to achieve the TMDL, and the proposed implementation plan comprises monitoring and surveillance only.

9. Surrounding Land Uses and Setting:

The North Bay segments are surrounded by developed urban areas including residential, commercial and industrial uses, forests and wetlands, open space and a small proportion of agricultural land.

10. Other public agencies whose approval is required (e.g., permits, financing approval)

The State Water Resources Control Board, the Office of Administrative Law, and the US Environmental Protection Agency must approve the proposed Basin Plan amendment.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
I. AESTHETICS: Would the project:				
a) Have a substantial adverse effect on a scenic vista	☐	☐	☐	☒
b) Substantially damage scenic resources, including, but not limited to, trees, rock outcroppings, and historic buildings within a state scenic highway	☐	☐	☐	☒
c) Substantially degrade the existing visual character or quality of the site and its surroundings?	☐	☐	☐	☒
d) Create a new source of substantial light or glare which would adversely affect day or nighttime views in the area?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no aesthetic impacts, because it would result in no direct or indirect change in the environment.

II. AGRICULTURE AND FOREST RESOURCES: In determining whether impacts to agricultural resources are significant environmental effects, lead agencies may refer to the California Agricultural Land Evaluation and Site Assessment Model (1997) prepared by the California Dept. of Conservation as an optional model to use in assessing impacts on agriculture and farmland. In determining whether impacts to forest resources, including timberland, are significant environmental effects, lead agencies may refer to information compiled by the California Department of Forestry and Fire Protection regarding the state's inventory of forest land, including the Forest and Range Assessment Project and the Forest Legacy Assessment Project; and the forest carbon measurement methodology provided in Forest Protocols adopted by the California Air Resources Board. Would the project:				
a) Convert Prime Farmland, Unique Farmland, or Farmland of Statewide Importance (Farmland), as shown on the maps prepared pursuant to the Farmland Mapping and Monitoring Program of the California Resources Agency, to non-agricultural use?	☐	☐	☐	☒
b) Conflict with existing zoning for agricultural use, or a Williamson Act contract?	☐	☐	☐	☒

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
c) Conflict with existing zoning for, or cause rezoning of, forest land (as defined in Public Resources Code section 12220(g)), timberland (as defined by Public Resources Code section 4526), or timberland zoned Timberland Production (as defined by Government Code section 51104(g))?	☐	☐	☐	☒
d) Result in the loss of forest land or conversion of forest land to non-forest use?	☐	☐	☐	☒
e) Involve other changes in the existing environment which, due to their location or nature, could result in conversion of Farmland, to non-agricultural use or conversion of forest land to non-forest use?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no agricultural and forest resource impacts. It would result in no change in land use or land use policy.

III. AIR QUALITY: Where available, the significance criteria established by the applicable air quality management or air pollution control district may be relied upon to make the following determinations. Would the project:				
a) Conflict with or obstruct implementation of the applicable air quality plan?	☐	☐	☐	☒
b) Violate any air quality standard or contribute substantially to an existing or projected air quality violation?	☐	☐	☐	☒
c) Result in a cumulatively considerable net increase of any criteria pollutant for which the project region is non- attainment under an applicable federal or state ambient air quality standard (including releasing emissions which exceed quantitative thresholds for ozone precursors)?	☐	☐	☐	☒
d) Expose sensitive receptors to substantial pollutant concentrations?	☐	☐	☐	☒
e) Create objectionable odors affecting a substantial number of people?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no air quality impacts, because it would result in no direct or indirect change in the environment.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
IV. BIOLOGICAL RESOURCES: Would the project:				
a) Have a substantial adverse effect, either directly or through habitat modifications, on any species identified as a candidate, sensitive, or special status species in local or regional plans, policies, or regulations, or by the California Department of Fish and Wildlife or U.S. Fish and Wildlife Service?	☐	☐	☐	☒
b) Have a substantial adverse effect on any riparian habitat or other sensitive natural community identified in local or regional plans, policies, and regulations or by the California Department of Fish and Wildlife or US Fish and Wildlife Service?	☐	☐	☐	☒
c) Have a substantial adverse effect on federally protected wetlands as defined by Section 404 of the Clean Water Act (including, but not limited to, marsh, vernal pool, coastal, etc.) through direct removal, filling, hydrological interruption, or other means?	☐	☐	☐	☒
d) Interfere substantially with the movement of any native resident or migratory fish or wildlife species or with established native resident or migratory wildlife corridors, or impede the use of native wildlife nursery sites?	☐	☐	☐	☒
e) Conflict with any local policies or ordinances protecting biological resources, such as a tree preservation policy or ordinance?	☐	☐	☐	☒
f) Conflict with the provisions of an adopted Habitat Conservation Plan, Natural Community Conservation Plan, or other approved local, regional, or state habitat conservation plan?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no adverse biological resource impacts, because it would result in no direct or indirect change in the environment.

V. CULTURAL RESOURCES: Would the project:	☐	☐	☐	☒
a) Cause a substantial adverse change in the significance of a historical resource as defined in §15064.5?	☐	☐	☐	☒

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
b) Cause a substantial adverse change in the significance of an archaeological resource pursuant to §15064.5?	☐	☐	☐	☒
c) Directly or indirectly destroy a unique paleontological resource or site or unique geologic feature?	☐	☐	☐	☒
d) Disturb any human remains, including those interred outside of formal cemeteries?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no impacts on cultural resources, because it would result in no construction projects or otherwise cause direct or indirect change in the environment.

VI. GEOLOGY AND SOILS: Would the project:

a) Expose people or structures to potential substantial adverse effects, including the risk of loss, injury, or death involving:	☐	☐	☐	☒
i) Rupture of a known earthquake fault, as delineated on the most recent Alquist-Priolo Earthquake Fault Zoning Map issued by the State Geologist for the area or based on other substantial evidence of a known fault? Refer to Division of Mines and Geology Special Publication 42?	☐	☐	☐	☒
ii) Strong seismic ground shaking?	☐	☐	☐	☒
iii) Seismic-related ground failure, including liquefaction?	☐	☐	☐	☒
iv) Landslides?	☐	☐	☐	☒
b) Result in substantial soil erosion or the loss of topsoil?	☐	☐	☐	☒
c) Be located on a geologic unit or soil that is unstable, or that would become unstable as a result of the project, and potentially result in on- or off-site landslide, lateral spreading, subsidence, liquefaction or collapse?	☐	☐	☐	☒
d) Be located on expansive soil, as defined in Table 18-1-B of the Uniform Building Code (1994), creating substantial risks to life or property?	☐	☐	☐	☒

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
e) Have soils incapable of adequately supporting the use of septic tanks or alternative waste water disposal systems where sewers are not available for the disposal of waste water?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no geologic or soil impacts, because it would result in no direct or indirect change in the environment.

VII. GREENHOUSE GAS EMISSIONS: Would the project:				
a) Generate greenhouse gas emissions, either directly or indirectly, that may have a significant impact on the environment?	☐	☐	☐	☒
b) Conflict with an applicable plan, policy, or regulation adopted for the purpose of reducing the emissions of greenhouse gases?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no greenhouse gas emission impacts, because it would result in no construction project or otherwise change the environment directly or indirectly.

VIII. HAZARDS AND HAZARDOUS MATERIALS: Would the project:				
a) Create a significant hazard to the public or the environment through the routine transport, use, or disposal of hazardous materials?	☐	☐	☐	☒
b) Create a significant hazard to the public or the environment through reasonably foreseeable upset and accident conditions involving the release of hazardous materials into the environment?	☐	☐	☐	☒
c) Emit hazardous emissions or handle hazardous or acutely hazardous materials, substances, or waste within one-quarter mile of an existing or proposed school?	☐	☐	☐	☒
d) Be located on a site which is included on a list of hazardous materials sites compiled pursuant to Government Code Section 65962.5 and, as a result, would it create a significant hazard to the public or the environment?	☐	☐	☐	☒

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
e) For a project located within an airport land use plan or, where such a plan has not been adopted, within two miles of a public airport or public use airport, would the project result in a safety hazard for people residing or working in the project area?	☐	☐	☐	☒
f) For a project within the vicinity of a private airstrip, would the project result in a safety hazard for people residing or working in the project area?	☐	☐	☐	☒
g) Impair implementation of or physically interfere with an adopted emergency response plan or emergency evacuation plan?	☐	☐	☐	☒
h) Expose people or structures to a significant risk of loss, injury or death involving wildland fires, including where wildlands are adjacent to urbanized areas or where residences are intermixed with wildlands?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no such impacts, because it would result in no direct or indirect change in the environment.

IX. HYDROLOGY AND WATER QUALITY: Would the project:	☐	☐	☐	☒
a) Violate any water quality standards or waste discharge requirements?	☐	☐	☐	☒
b) Substantially deplete groundwater supplies or interfere substantially with groundwater recharge such that there would be a net deficit in aquifer volume or a lowering of the local groundwater table level (e.g., the production rate of pre-existing nearby wells would drop to a level which would not support existing land uses or planned uses for which permits have been granted)?	☐	☐	☐	☒
c) Substantially alter the existing drainage pattern of the site or area, including through the alteration of the course of a stream or river, in a manner which would result in substantial erosion or siltation on- or off-site?	☐	☐	☐	☒
d) Substantially alter the existing drainage pattern of the site or area, including through the alteration of the course of a stream or river, or substantially increase the rate or amount of surface runoff in a manner which would result in flooding on- or off-site?	☐	☐	☐	☒

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
e) Create or contribute runoff water which would exceed the capacity of existing or planned stormwater drainage systems or provide substantial additional sources of polluted runoff?	☐	☐	☐	☒
f) Otherwise substantially degrade water quality?	☐	☐	☐	☒
g) Place housing within a 100-year flood hazard area as mapped on a federal Flood Hazard Boundary or Flood Insurance Rate Map or other flood hazard delineation map?	☐	☐	☐	☒
h) Place within a 100-year flood hazard area structures which would impede or redirect flood flows?	☐	☐	☐	☒
i) Expose people or structures to a significant risk of loss, injury or death involving flooding, including flooding as a result of the failure of a levee or dam?	☐	☐	☐	☒
j) Inundation by seiche, tsunami, or mudflow	☐	☐	☐	☒

This proposed Basin Plan amendment would have no impacts to hydrogeology or water quality, because it would result in no direct or indirect change in the environment.

X. LAND USE AND PLANNING: Would the project:

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
a) Physically divide an established community?	☐	☐	☐	☒
b)Conflict with any applicable land use plan, policy, or regulation of an agency with jurisdiction over the project (including, but not limited to the general plan, specific plan, local coastal program, or zoning ordinance) adopted for the purpose of avoiding or mitigating an environmental effect?	☐	☐	☐	☒
c) Conflict with any applicable habitat conservation plan or natural community conservation plan?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no land use impacts. The proposed action would not create or change any policy or program, nor will it result in no direct or indirect change in the environment.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
XI. MINERAL RESOURCES: Would the project:				
a) Result in the loss of availability of a known mineral resource that would be of value to the region and the residents of the state?	☐	☐	☐	☒
b) Result in the loss of availability of a locally-important mineral resource recovery site delineated on a local general plan, specific plan or other land use plan?	☐	☐	☐	☒

No mineral resources would be affected by the proposed action.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
XII. NOISE: Would the project result in:				
a) Exposure of persons to or generation of noise levels in excess of standards established in the local general plan or noise ordinance, or applicable standards of other agencies?	☐	☐	☐	☒
b) Exposure of persons to or generation of excessive groundborne vibration or groundborne noise levels?	☐	☐	☐	☒
c) A substantial permanent increase in ambient noise levels in the project vicinity above levels existing without the project?	☐	☐	☐	☒
d) A substantial temporary or periodic increase in ambient noise levels in the project vicinity above levels existing without the project?	☐	☐	☐	☒
e) For a project located within an airport land use plan or, where such a plan has not been adopted, within two miles of a public airport or public use airport, would the project expose people residing or working in the project area to excessive noise levels?	☐	☐	☐	☒
f) For a project within the vicinity of a private airstrip, would the project expose people residing or working in the project area to excessive noise levels?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no noise impacts.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
XIII. POPULATION AND HOUSING: Would the project:				
a) Induce substantial population growth in an area, either directly (for example, by proposing new homes and businesses) or indirectly (for example, through extension of roads or other infrastructure)?	☐	☐	☐	☒
b) Displace substantial numbers of existing housing, necessitating the construction of replacement housing elsewhere?	☐	☐	☐	☒
c) Displace substantial numbers of people, necessitating the construction of replacement housing elsewhere?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no impacts on population and/or housing; it would result in no direct or indirect change in the environment; and it will not create or change any plan, policy or program.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
XIV. PUBLIC SERVICES:				
a) Would the project result in substantial adverse physical impacts associated with the provision of new or physically altered governmental facilities, need for new or physically altered governmental facilities, the construction of which could cause significant environmental impacts, in order to maintain acceptable service ratios, response times or other performance objectives for any of the public services:	☐	☐	☐	☒
Fire protection?	☐	☐	☐	☒
Police protection?	☐	☐	☐	☒
Schools?	☐	☐	☐	☒
Parks?	☐	☐	☐	☒
Other public facilities?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no impact on public services, and it would result in no need to alter or construct governmental facilities.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
XV. RECREATION:				
a) Would the project increase the use of existing neighborhood and regional parks or other recreational facilities such that substantial physical deterioration of the facility would occur or be accelerated?	☐	☐	☐	☒
b) Does the project include recreational facilities or require the construction or expansion of recreational facilities which might have an adverse physical effect on the environment?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no impact on the demand or need for recreational facilities.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
XVI. TRANSPORTATION/TRAFFIC: Would the project:				
a) Conflict with an applicable plan, ordinance or policy establishing measures of effectiveness for the performance of the circulation system, taking into account all modes of transportation including mass transit and non-motorized travel and relevant components of the circulation system, including but not limited to intersections, streets, highways and freeways, pedestrian and bicycle paths, and mass transit?	☐	☐	☐	☒
b) Conflict with an applicable congestion management program, including, but not limited to level of service standards and travel demand measures, or other standards established by the county congestion management agency for designated roads or highways?	☐	☐	☐	☒
c) Result in a change in air traffic patterns, including either an increase in traffic levels or a change in location that results in substantial safety risks?	☐	☐	☐	☒
d) Substantially increase hazards due to a design feature (e.g., sharp curves or dangerous intersections) or incompatible uses (e.g., farm equipment)?	☐	☐	☐	☒

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
e) Result in inadequate emergency access?	☐	☐	☐	☒
f) Conflict with adopted policies, plans or programs regarding public transit, bicycle, or pedestrian facilities, or otherwise decrease the performance or safety of such facilities?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no transportation impacts, because it would result in no direct or indirect change in the environment. Nor would the proposed action change any policy, plan, or program.

XVII. UTILITIES AND SERVICE SYSTEMS: Would the project:

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
a) Exceed wastewater treatment requirements of the applicable Regional Water Quality Control Board?	☐	☐	☐	☒
b) Require or result in the construction of new water or wastewater treatment facilities or expansion of existing facilities, the construction of which could cause significant environmental effects?	☐	☐	☐	☒
c) Require or result in the construction of new storm water drainage facilities or expansion of existing facilities, the construction of which could cause significant environmental effects?	☐	☐	☐	☒
d) Have sufficient water supplies available to serve the project from existing entitlements and resources, or are new or expanded entitlements needed?	☐	☐	☐	☒
e) Result in a determination by the wastewater treatment provider which serves or may serve the project that it has adequate capacity to serve the project's projected demand in addition to the provider's existing commitments?	☐	☐	☐	☒
f) Be served by a landfill with sufficient permitted capacity to accommodate the project's solid waste disposal needs?	☐	☐	☐	☒
g) Comply with federal, state, and local statutes and regulations related to solid waste?	☐	☐	☐	☒

This proposed Basin Plan amendment would have no impacts on utilities and service systems.

	Potentially Significant Impact	Less Than Significant with Mitigation	Less Than Significant Impact	No Impact
XVIII. MANDATORY FINDINGS OF SIGNIFICANCE				
a) Does the project have the potential to degrade the quality of the environment, substantially reduce the habitat of a fish or wildlife species, cause a fish or wildlife population to drop below self-sustaining levels, threaten to eliminate a plant or animal community, substantially reduce the number or restrict the range of a rare or endangered plant or animal or eliminate important examples of the major periods of California history or prehistory?	☐	☐	☐	☒
b) Does the project have impacts that are individually limited, but cumulatively considerable? ("Cumulatively considerable" means that the incremental effects of a project are considerable when viewed in connection with the effects of past projects, the effects of other current projects, and the effects of probable future projects)?	☐	☐	☐	☒
c) Does the project have environmental effects which will cause substantial adverse effects on human beings, either directly or indirectly?	☐	☐	☐	☒

This proposed Basin Plan amendment aims at protecting water quality and would have no direct or indirect impact on the environment, including aquatic and terrestrial wildlife and flora and humans.

9.3 Consideration of Alternatives

As explained in this report, the proposed project will not have any significant adverse impacts to the environment; therefore, alternatives beyond the No Project alternative are not explored. In addition, the only new compliance action is monitoring, which does not involve any direct or indirect impacts on the environment.

Though an alternative analysis is not required, we provide a discussion of the No Project alternative to illustrate that the proposed project would be environmentally beneficial and because the only alternative for the proposed project is the No Project alternative.

Alternative: No Project

Under this alternative, the Water Board would not amend the Basin Plan to establish fish-tissue and water column targets and associated selenium TMDL and allocations, and would not limit selenium loads from point and non-point sources at environmentally protective levels.

The No Project alternative would not set targets, nor would it ensure that monitoring will continue to demonstrate achievement of those targets or protection of beneficial uses. The RMP may continue to collect and evaluate data on the status and trends of selenium in San Francisco Bay. The No Project alternative would not meet the project objectives of addressing the CWA section 303(d) listing. It would not establish a selenium TMDL protective of beneficial uses.

Nor would it meet the objective to ensure ongoing protection of existing water quality and prevent the risk of selenium bioaccumulation in clam-eating fish.

Therefore, Water Board staff rejected this alternative because it is not an environmentally superior alternative nor does it meet the project objectives, including the following:

- Establish an approach for determining the permit effluent limits protective of aquatic life in the North Bay;
- Determine the amount of selenium that the North Bay could receive and still ensure protection of aquatic life beneficial uses; and
- Establish selenium loads at environmentally sensitive levels and track inflows of selenium from San Joaquin River.

Preferred Alternative

The proposed Basin Plan amendment meets all the project objectives and will not result in any significant adverse environmental impacts. The alternative does not meet all the project objectives and is not environmentally superior. Therefore, the proposed Basin Plan amendment is the preferred alternative.

9.4 Economic Considerations

CEQA requires that whenever one of California's nine Regional Water Quality Control Boards, such as the San Francisco Bay Regional Water Quality Control Board (Water

Board), adopts a rule that requires the installation of pollution control equipment or establishes a performance standard or treatment requirement, it must conduct an environmental analysis for reasonably foreseeable methods of compliance (Pub. Res. Code § 2759, subd. (a)(3)(c)).

The proposed Basin Plan amendment for the North San Francisco Bay is based on current performance and as such it does not require the installation of pollution control equipment or changes to the level of treatment already used by petroleum refineries and other municipal and industrial treatment facilities, therefore the consideration of economic factors is not necessary.

The monitoring required by this project is ongoing. The Regional Monitoring Program (RMP) conducted by the San Francisco Estuary Institute collects much of the data that are required as part of the ongoing assessment of the health of the Bay, including selenium concentrations in water, sediment and fish. Maintaining this effort will not incur any additional cost, and therefore does not require an economic analysis. The cost of monitoring selenium in San Joaquin River inflow into the Bay is insignificant compared to the monitoring already in place or planned to be implemented in the near future.

10 References

Abu-Saba, K. and S. Ogle. 2005. *selenium in San Francisco Bay: Conceptual Model/Impairment Assessment*. Report prepared for the Clean Estuary Partnership, June 2005.

Adams, W.J., Brix, K.V., Edwards, M., Tear, L.M., Deforest, D.K. and A. Fairbrother. 2003. "Analysis of field and laboratory data to derive selenium toxicity thresholds for birds". *Environmental Toxicology and Chemistry* 22(9): 2020–2029.

Amweg, E.L., Stuart, D.L. and D.P. Weston. 2003. "Comparative bioavailability of selenium to aquatic organisms after biological treatment of agricultural drainage water". *Aquatic Toxicology* 63: 13–25.

Badzinski, S.S., Flint, P.L., Gorman, K.B. and S.A. Petrie. 2009. "Relationships between hepatic trace element concentrations, reproductive status, and body condition of female greater scaup". *Environmental Pollution*. 157, 1886-1893.

Baines, S.B. and N.S. Fisher. 2001. "Interspecific differences in the bioconcentration of selenite by phytoplankton and their ecological implications". *Marine Ecology Progress Series*, 213: 1–12.

Baines, S.B., Fisher, N.S., Doblin, M.A., Cutter, G.A., Cutter, L.S. and B.E. Cole. 2004. "Light dependence of selenium uptake by phytoplankton and implications for predicting selenium incorporation into food webs". *Limnology and Oceanography* 49(2): 566–578.

BASMAA (Bay Area Stormwater Management Agencies Association). 1996. *San Francisco Bay Area Stormwater Runoff Monitoring Data Analysis 1988-1995.* Final Report prepared by Woodward-Clyde.

BASMAA (Bay Area Stormwater Management Agencies Association). 2013. *Regional Monitoring Coalition Urban Creeks Monitoring Report Water Year 2012* http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/stormwater/UC_Monitoring_Report_2012.pdf .

Beckon, W.N. 2007. Selenium risk to salmonids with particular reference to the Central Valley of California. Poster presented at the American Fisheries Society Meeting, September 2007, San Francisco.

Beckon, W.N. and T.C. Maurer. 2008. *Species at Risk from selenium Exposure in the San Francisco Estuary.* Unpublished report prepared for the U.S. Environmental Protection Agency.

Canton, S.P. and W.D. Van Derveer. 1997. "Selenium toxicity to aquatic life: An argument for sediment-based water quality criteria". *Environmental Toxicology and Chemistry* 16(6): 1255–1259.

Chapman, P.M. 2007. "Selenium thresholds to fish from cold freshwaters". *Human and Ecological Risk Assessment*, 13: 20–24.

Chapman, P.M., Adams, W.J., Brooks, M.L., Delos, C.G., Luoma, S.N., Maher, W.A., Ohlendorf, H.M., Presser, T.S., and D.P. Shaw (eds). 2009. Ecological Assessment of selenium in the Aquatic Environment. Summary of the SETAC Pellston Workshop, Pensacola, Florida.

Chen, L., Meseck, S.L., Roy, S.B., Grieb, T.M. and B. Baginska. 2012. "Modeling fate, transport, and biological uptake of selenium in North San Francisco Bay". *Estuaries and Coasts,* v. 35 (6): 1551-1570

Cloern, J.E., Jassby, A.D., Thompson, J.K. and K.A. Hieb. 2007. "A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay". Proceedings of the National Academy of Sciences USA, v. 104, 18561–18565 (published with Open Access).

Cohen, A. 2000. *An Introduction to the San Francisco Estuary*. Save The Bay, San Francisco Estuary Institute. 41 pp.

Conomos, T.J., Smith, R.E. and J.W. Gartner. 1985. Environmental Setting of San Francisco Bay. *Hydrobiologia,* 129:1–12

Cutter, G.A. 1992. "Kinetic controls on metalloid speciation in seawater". *Marine Chemistry*, 40, 65–80.

Cutter, G.A. and T.M. Church. 1986. "Selenium in western Atlantic precipitation". *Nature*, 322 (6081): 720–722.

Cutter, G.A. and L.S. Cutter. 2004. "Selenium biogeochemistry in the San Francisco Bay estuary: changes in water column behavior". *Estuarine, Coastal and Shelf Science* 61: 463–476.

Cutter, G.A. and M.L.C. San Diego-McGlone. 1990. "Temporal variability of selenium fluxes in San Francisco Bay". *Science of the Total Environment,* 97/98: 235–250.

David, N., Gluchowski, D.C, Leatherbarrow, J.E, Yee, D. and McKee, L.J. 2012. *Evaluation of Loads of Mercury, Selenium, PCBs, PAHs, PBDEs, Dioxins, and Organochlorine Pesticides from the Sacramento-San Joaquin River Delta to San Francisco Bay*. SFEI Contribution #681. San Francisco Estuary Institute, Oakland, CA. 49 pp. http://www.sfei.org/sites/default/files/Mallard_Island_Report_120216.pdf

Davis, J.A., McKee, L.J., Leatherbarrow, J.E. and T.H. Daum. 2000. *From Stormwater to Coastal Waters in the San Francisco Bay Region. Comparison to other pathways and recommended approach for future evaluation*. San Francisco Estuary Institute, September 2000.

Davis, J.A., K. Schiff, A.R. Melwani, S.N. Bezalel, J.A. Hunt, R.M. Allen, G. Ichikawa, A. Bonnema, W.A. Heim, D. Crane, S. Swenson, C. Lamerdin, and M. Stephenson. 2011. *Contaminants in Sport Fish from the California Coast, 2009: Summary Report on Year One of a Two-Year Screening Survey*. Surface Waters Ambient Monitoring Program.

Deng, D-F., Hung, S.S.O. and S.J. The. 2007. "Selenium depuration: Residual effects of dietary selenium on Sacramento splittail (*Pogonichthys macrolepidotus*)". *Science of the Total Environment* 377: 224–232.

DeVink, J.M., Clark, R., Slattery, S. and T.M. Scheuhammer. 2008. "Effects of dietary selenium on reproduction and body mass of captive lesser scaup". *Environmental Toxicology and Chemistry*, 27(2): 471–477.

DFG (California Department of Fish and Game). 1987. *Selenium Verification Study 1986*. Report prepared for the California State Water Resources Control Board, May 1987.

DFG (California Department of Fish and Game). 1988. *Selenium Verification Study 1986-1987*. Report prepared for the California State Water Resources Control Board, February 1988.

DFG (California Department of Fish and Game). 1991. *Selenium Verification Study 1988-1990*. Report prepared for the California State Water Resources Control Board, May 1991.

Doblin, M.A., Baines, S.B., Cutter, L.S. and G.A. Cutter. 2006. "Sources and biogeochemical cycling of particulate selenium in the San Francisco Bay estuary". *Estuarine, Coastal and Shelf Science* 67: 681–694.

Eisler, R. 1985. *Selenium Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review*. US Fish and Wildlife Service, Biological Report No. 85(1.5).

Fairbrother, A., Brix, K.V., Tollt, J.E, McKay, S. and W.J. Adams. 1999. "Egg selenium concentrations as predictors of avian toxicity". *Human and Ecological Risk Assessment* 5: 1229–1253.

Fan, T.W-M., Teh, S.J., Hinton, D.E. and R.M. Higashi. 2002. "Selenium biotransformations into proteinaceous forms by foodweb organisms of selenium laden drainage waters in California". *Aquatic Toxicology* 57: 65–84.

Federal Register. 2000. *Water Quality Standards; Establishment of Numeric Criteria for Priority Toxic Pollutants for the State of California. Final Rule.* 6587-9 Vol. 65, No. 97.

Federal Register. 2008. *Endangered and Threatened Wildlife and Plants: Proposed Rulemaking To Designate Critical Habitat for the Threatened Southern Distinct Population Segment of North American Green Sturgeon; Proposed Rule.* 52084 Vol. 73, No. 174.

Feyrer, F., Herbold, B., Matern, S.A. and P.B. Moyle. 2003 "Dietary shifts in a stressed fish assemblage: Consequences of a bivalve invasion in the San Francisco Estuary". *Environmental Biology of Fishes* 67: 277–288.

Hamilton, S.J. 2002. "Rationale for a tissue-based selenium criterion for aquatic life". *Aquatic Toxicology* 57, 85–100.

Hamilton, S.J. 2003. "Review of residue-based selenium toxicity thresholds for freshwater fish". *Ecotoxicology and Environmental Safety* 56: 201–210.

Hamilton, S.J. 2004. "Review of selenium toxicity in the aquatic food chain". *Science of the Total Environment* 326: 1–31.

Hamilton, S.J. and K.J. Buhl. 1990. "Acute toxicity of boron, molybdenum, and selenium to fry of Chinook salmon and Coho salmon". *Archives of Environmental Contamination and Toxicology*, 19 (3): 366–373.

Hamilton, S.J., Buhl, K.J., Faerber, N.L., Wiedmeyer, R.H. and F.A. Bullard. 1990. "Toxicity of organic selenium in the diet to Chinook salmon". *Environmental Toxicology and Chemistry* 9: 347–358.

Hansen, L.D., Maier, K.J. and A.W. Knight. 1993. "The effect of sulfate on the bioconcentration of selenate by *Chironomus decorus* and *Daphnia magna*". *Archives of Environmental Contamination and Toxicology* 25: 72–78.

Hardy, R.W., Oram, L.L. and G. Möller. 2010. "Effects of dietary selenomethionine on cutthroat trout (*Oncorhynchus clarki bouvieri*) growth and reproductive performance over a life cycle". *Archives of Environmental Contamination and Toxicology* 58: 237–245.

Harris, J.R.W., and R.N. Gorley. 1998. *An introduction to modeling estuaries with ECoS 3*. Plymouth Marine Laboratory.

Heinz, G.H., Pendleton, G.W., Krynitsky, A.J. and L.G. Gold. 1990. "Selenium accumulation and elimination in mallards". *Archives of Environmental Contamination and Toxicology* 19: 374–379.

Hem, J.D. 1985. *Study and Interpretation of Chemical Characteristics of Natural Water*: U.S. Geological Survey Water-Supply Paper 2254. Table 2, p.7.

Ihnat, M. 1989. Occurrence and Distribution of selenium. CRC Press, Boca Raton, Fla. p.221.

Israel, J.A., Drauch, A.M., Gingras, M. and M.Donnellan. 2010. *Life History Conceptual Model for White Sturgeon (Acipenser transmontanus).* CDFG Delta Regional Ecosystem Restoration and Implementation Program. FINAL, 55 pp. http://www.dfg.ca.gov/erp/cm_list.asp .

Janz, D.M., Liber, K., Pickering, I.J., Wiramanaden, C., Weech, S.A., Gallego-Gallegos, M., Driessnack, M.K., Franz, E.D., Goertzen, M.M., Phibbs, J., Tse, J.J., Himbeault, K.T., Robertson, E.L., Burnett-Seidel, C., England, K. and A. Genty. 2014. “Integrative assessment of selenium speciation, biogeochemistry, and distribution in a northern coldwater ecosystem”. *Integrated Environmental Assessment and Management* 10(4): 543–554.

Kaufman, R.C., Houck, A.G. and J.J. Cech Jr. 2008. Effects of dietary selenium and methylmercury on green and white sturgeon bioenergetics in response to changed environmental conditions. Presentation at the 5th Biennial CALFED Science Conference, October 22-24, 2008, Sacramento, CA.

Kleckner, A.E., Stewart, A.R., Elrick, K., and S.N.Luoma. 2010. *Selenium concentrations and stable isotopic compositions of carbon and nitrogen in the benthic clam Corbula amurensis from Northern San Francisco Bay, California: May 1995–February 2010*: U.S. Geological Survey Open-File Report 2010-1252, 34 p.

Kogut, N.J. 2008. “Overbite clams, *Corbula amurensis*, defecated alive by white sturgeon, *Acipenser transmontanus*.” *California Fish and Game*, 94(3): 143–149.

Lee, B.G., Lee, J.S. and S.N. Luoma. 2006. “Comparison of selenium bioaccumulation in the clams *Corbicula fluminea* and *Potamocorbula amurensis*: a bioenergetic modeling approach.” *Environmental Toxicology and Chemistry*, 25(7): 1933–1940.

Lemly, A.D. 1997. “Environmental implications of excessive selenium: A Review”. *Biomedical and Environmental Sciences* 10: 415–435.

Lemly, A.D. 1998. “A Position Paper on Selenium in Ecotoxicology: A Procedure for deriving site-specific water quality criteria”. *Ecotoxicology and Environmental Safety* 39: 1–9.

Lemly, A.D. 1999. “Selenium transport and bioaccumulation in aquatic ecosystems: A proposal for water quality criteria based on hydrological units”. *Ecotoxicology and Environmental Safety* 42: 150–156.

Linares, J., Linville, R., Van Eenennaam, J. and S. Doroshov. 2004. *Selenium Effects on Health and Reproduction of White Sturgeon in the Sacramento-San Joaquin Estuary.* Final Report for Project No. ERP-02-P35 (contract No. 4600002881). 57 pp.

Linares-Casenave, J., Linville, R., Van Eenennaam, J.P., Muguet, J.B. and Sl. Doroshov. 2015. “Selenium tissue burden compartmentalization in resident white sturgeon (*Acipenser transmontanus*) of the San Francisco Bay Delta estuary”. *Environmental Toxicology and Chemistry*, 34(1):152-160.

Linville, R.G. 2006. *Effects of Excess Selenium on the Health and Reproduction of White Sturgeon (Acipenser transmontanus): Implications for San Francisco Bay-Delta.* PhD Dissertation. University of California, Davis. 232 pp.

Linville, R.G., Luoma, S.N., Cutter L., and G.A. Cutter. 2002. “Increased selenium threat as a result of invasion of the exotic bivalve *C. amurensis* into the San Francisco Bay-Delta”. *Aquatic Toxicology* 57: 51–64.

Luoma, S.N., Johns, C., Fisher, N.S., Steinberg, N.A., Oremland, R.S. and J.R. Reinfelder. 1992. “Determination of selenium bioavailability to a benthic bivalve from particulate and solute pathways”. *Environmental Science Technology*, 26: 485–491.

Luoma., S.N. and T.S. Presser. 2009. “Emerging opportunities in management of selenium contamination”. *Environmental Science and Technology,* 43: 8483–8487.

Luoma, S.N. and P.S. Rainbow. 2008. Metal Contamination in Aquatic Environments. Science and Lateral Management. Chapter 13: *Selenium: dietary exposure, trophic transfer and food web effects*. 327–353. Cambridge University Press, New York.

MacFarlane, B.R. and E.C. Norton. 2002. “Physiological ecology of juvenile chinook salmon (*Oncorhynchus tshawytscha*) at the southern end of their distribution, the San Francisco Estuary and Gulf of the Farallones, California”. *Fishery Bulletin,* 100: 244–257.

McKee, L.J., Ganju, N.K. and D.H. Schoellhamer. 2006. “Estimates of suspended sediment entering San Francisco Bay from the Sacramento and San Joaquin Delta, San Francisco Bay, California”. *Journal of Hydrology,* 323: 335–352.

McKee, L.J., Leatherbarrow, J., Newland, S. and J. Davis. 2003. *A Review of Urban Runoff Processes in the Bay Area: Existing Knowledge, Conceptual Models, and Monitoring Recommendations.* A report prepared for the RMP Sources, Pathways and Loading Workgroup. SFEI Contribution Number 66. San Francisco Estuary Institute, Oakland, CA.

Meseck, S.L. 2002. Modeling the Biogeochemical Cycle of Selenium in the San Francisco Bay. PhD Dissertation, Old Dominion University.

Meseck, S.L. and G.A.Cutter, 2006. “Evaluating the biogeochemical cycle of selenium in San Francisco Bay through modeling”. *Limnology and Oceanography,* 51(5): 2018–2032.

Meseck, S.L. and G.A.Cutter, 2012. “Selenium behavior in San Francisco Bay sediments”. *Estuaries and Coasts*, 35: 646–657.

Mosher B.W. and R.A. Duce. 1989. The Atmosphere, in *Occurrence and Distribution of selenium*, Ed. by Milan Ihnat, CRC Press, Inc. Florida, 309 pp.

Moyle, P.B, Baxter, R.D., Sommer, T., Foin T.C. and S.A. Matern. 2004. “Biology and population dynamics of Sacramento Splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: A Review”. *San Francisco Estuary and Watershed Science*, 2 (2). http://escholarship.org/uc/jmie_sfews?volume=2;issue=2

OEHHA (Office of Environmental Health Hazard Assessment) 2008. *Development of Fish Contaminant Goals and Advisory Tissue Levels for Common Contaminants in California Sport Fish: Chlordane, DDTs, Dieldrin, Methylmercury, PCBs, Selenium and Toxaphene.* June 2008.

Ohlendorf, H.M. and W.J. Fleming. 1988. “Birds and environmental contaminants in San Francisco and Chesapeake Bays”. *Marine Pollution Bulletin,* 19(9): 487–495.

Parchaso, F., and J.K. Thompson. 2002. “Influence of hydrologic processes on reproduction of the introduced bivalve *Potamocorbula amurensis* in northern San Francisco Bay, California”. *Pacific Science* 56 (3): 329–345.

Paveglio, F.L. and K.M. Kilbride. 2007. “Selenium in aquatic birds from Central California”. *The Journal of Wildlife Management,* 71(8): 2550–2555.

Poulton, V.K., Lovvorn, J.R. and J.Y. Takekawa. 2004. “Spatial and overwinter changes in clam populations of San Pablo Bay, a semiarid estuary with highly variable freshwater inflow”. *Estuarine, Coastal and Shelf Science,* 59: 459–473.

Presser, T.S. 1994. Geologic Origin and Pathways of Selenium from the California Coast Ranges to the West-Central San Joaquin Valley. In *Selenium in the Environment*, ed. W.T. Frankenberger, Jr. and S. Benson, 139–155. Marcel Dekker, Inc. New York.

Presser, T.S. 2013. Selenium in Ecosystems within the Mountaintop Coal Mining and Valley-Fill Region of Southern West Virginia–Assessment and Ecosystem-Scale Modeling: U.S. Geological Survey Professional Paper 1803, 86 pp. (http://dx.doi.org/10.3133/pp1803) .

Presser, T.S. and S.N. Luoma. 2006. *Forecasting Selenium Discharges to the San Francisco Bay-Delta Estuary: Ecological Effects of a Proposed San Luis Drain Extension*. U.S. Geological Survey Professional Paper 1646.

Presser, T.S. and S.N. Luoma. 2009. *Modeling of Selenium for the San Diego Creek Watershed and Newport Bay, California.* U.S. Geological Survey Open-File Report 1114.

Presser, T.S. and S.N. Luoma. 2010a. "A methodology for ecosystem-scale modeling of selenium". *Integrated Environmental Assessment and Management*, Vol. 6, 685–710. Supporting Material http://wwwrcamnl.wr.usgs.gov/Selenium/Library_articles/Presser_Luoma_2010_IEAMv6no4_supporting.pdf

Presser, T.S. and S.N. Luoma. 2010b. *Ecosystem-Scale Selenium Modeling in Support of Fish and Wildlife Criteria Development for the San Francisco Bay-Delta Estuary, California.* Administrative Report to USEPA, December 2010. http://www.epa.gov/region9/water/ctr/Se-modeling_admin-report.pdf

Presser, T.S. and S.N. Luoma. 2013. "Ecosystem-scale selenium model for the San Francisco Bay-Delta Regional Ecosystem Restoration Implementation Plan". *San Francisco Estuary and Watershed Science,* 11(1). http://www.escholarship.org/uc/item/2td0b99t

Presser, T.S., Luoma, S.N. and E.E. McNaughton. 2008. *Aquatic Ecosystem-Scale Selenium Modeling for Invertebrates, Fish and Birds.* Presentation at the Nov 2008 SETAC Meeting.

Rayman, M.P. 2000. "The importance of selenium to human health". *The Lancet*, Vol. 15, Issue 9225, 233–241.

Riedel, G.F., Sanders, J.G. and C.C. Gilmour. 1996. "Uptake, transformation, and impact of selenium in freshwater phytoplankton and bacterioplankton communities". *Aquatic Microbial Ecology* 11: 43–51.

Sample, B.E. and C.A. Arenal. 1999. "Allometric models for interspecies extrapolation of wildlife toxicity data." *Environmental Contamination and Toxicology*, 62: 653–663.

Schlekat, C.E., Purkerson, D.G. and S.N. Luoma. 2004. "Modeling selenium bioaccumulation through arthropod food webs in San Francisco Bay, California, USA". *Environmental Toxicology and Chemistry* 23(12): 3003–3010.

Schlenk, D., Zubcov, N. and E. Zubcov. 2003. "Effects of salinity on the uptake, biotransformation, and toxicity of dietary seleno-l-methionine to rainbow trout". *Toxicological Sciences* 75: 309–313.

Schwarzbach, S.E., Albertson, J.D. and C.M. Thomas. 2006. "Effects of predation, flooding and contamination on reproductive success of California Clapper Rails *(Rallus Longirostris Obsoletus)* in San Francisco Bay". *The Auk* 123(1):45–60.

Seiler, R.L., Skorupa, J.P., Naftz, D.L. and B.T. Nolan. 2003. *Irrigation-Induced Contamination of Water, Sediment, and Biota in the Western United States – Synthesis of the Data from the National Irrigation Water Quality Program*. U.S. Geological Survey Professional Paper 1655, pp 123.

SFEI (San Francisco Estuary Institute). 2000. *San Francisco Bay Seafood Consumption Study*. San Francisco Estuary Institute, Richmond, CA.

SFEP (San Francisco Estuary Partnership). 1992. *State of the Estuary – A Report on Conditions and Problems in the San Francisco Bay/Sacramento – San Joaquin Delta Estuary.*

SFBRWQCB (San Francisco Regional Water Quality Control Board). 2007a. *Water quality monitoring and bioassessment in nine San Francisco Bay Region watersheds in 2001-2003: Walker Creek, Lagunitas Creek, San Leandro Creek, Wildcat Creek/San Pablo Creek, Suisun Creek, Arroyo Las Positas, Pescadero Creek/Butano Creek, San Gregorio Creek, and Stevens Creek/Permanente Creek*. Project Report. Surface Water Ambient Monitoring Program, Oakland, CA:

SFBRWQCB (San Francisco Regional Water Quality Control Board). 2007b. *Water Quality Monitoring and Bioassessment in Four San Francisco Bay Region Watersheds in 2003-2004: Kirker Creek, Mt. Diablo Creek, Petaluma River, and San Mateo Creek.* Project Report. Surface Water Ambient Monitoring Program, Oakland, CA.

Skorupa, J.P. 1998. Selenium Poisoning of Fish and Wildlife in Nature: Lessons from Twelve Real-World Examples. In *Environmental Chemistry of Selenium*, ed. W.T. Frankenberger, Jr. and R.A. Engberg, 315–354. Marcel Dekker, Inc. New York.

Skorupa, J.P. and H.M. Ohlendorf. 1991. Contaminants in Drainage Water and Avian Risk Thresholds. In *The Economics and Management of Water and Drainage in Agriculture*, ed. A. Dinar and D. Zilberman, 345–368. Kluwer Academic Publishers, Boston.

Stewart, A.R., Luoma, S.N., Schlekat, C.E., Doblin, M.A. and K.A. Hieb. 2004. “Food web pathway determines how selenium affects aquatic ecosystems: A San Francisco Bay case study”. *Environmental Science and Technology* 38: 4519–4526.

Stewart, A.R., Luoma, S.N., Elrick, K.A., Carter, J.L. and M. Van der Wegen. 2013. “Influence of estuarine processes on spatiotemporal variation in bioavailable selenium”. *Marine Ecology Progress Series*, 492: 41–56.

Sweet, C.W., Weiss, A. and S.J. Vermette. 1998. "Atmospheric deposition of trace metals at three sites near the great lakes." *Water, Air, and Soil Pollution*, 103(1-4): 423–439.

SWRCB (State Water Resources Control Board). 1988. *Selenium in California.* Volume 1 – History, Chemistry, Biology, Uses, Management. 88-10-I-WR. Reprinted October 1990. 83–95.

Tashijan, D.H., Teh, S.J., Sogomonyan, A. and S.S.O. Hung. 2006. "Bioaccumulation and chronic toxicity of dietary L-selenomethionine in juvenile white sturgeon (*Acipenser transmontanus)*". *Aquatic Toxicology* 79: 401–409.

Teh, S.J., Deng, X., Deng, D.-F., Teh, F.-C., Hung, S.S.O., Fan, T.W-M., Liu, J. and R.M. Higashi. 2004. "Chronic effects of dietary selenium on juvenile Sacramento splittail (*Pogonichthys macrolepidotus*)".*Environmental Science and Technology*, 38 (22): 6085–6093.

Tetra Tech, Inc. 2008a. Technical Memorandum 2: *North San Francisco Bay Selenium Data Summary and Source Analysis.* July 2008. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2008b. Technical Memorandum 3: *North San Francisco Bay Selenium Toxicological Assessment.* April 2008. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2008c. Technical Memorandum 4: *Conceptual Model of Selenium in North San Francisco Bay*. August 2008. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2008d. Technical Memorandum 5: *Recommendations for Numerical Model Development*. August 2008. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2010. Technical Memorandum 6: *Application of ECoS3 Model for Simulation of Selenium Fate and Transport in North San Francisco Bay*. February 2010. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2012. *North San Francisco Bay Selenium Characterization Study*. Final Report. October 2012. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2013. *Evaluation of an Alternative Selenium Regulatory Criterion Value*. Technical Memorandum. January 2013. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2014. *Calculating Dissolved Selenium Loads from the Delta to San Francisco Bay Using DSM2.* May 2014. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

Tetra Tech, Inc. 2015. *Updates to ECoS3 to Simulate Selenium Fate and Transport in North San Francisco Bay.* February 2015. http://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/Setmdl.shtml

URS. 2007. *Status and Trends of Delta-Suisun Services.* Report was for the Department of Water Resources. Chapter 2. Status of Services: Water Supply, 18–21.

USDOI (U.S. Department of Interior). 1998. Guidelines for the Interpretation of the Biological Effects of Selected Constituents in Biota, Water, and Sediment. National Irrigation Quality Program Information Report No. 3.

USDHHS (U.S. Department of Health and Human Services). 2003. *Toxicological Profile for Selenium.* Chapter 6. Potential for Human Exposure, 235–252.

USEPA (U.S. Environmental Protection Agency). 1996. *Chesapeake Bay Atmospheric Deposition Study*. Final Report. USEPA-903-R-96-005.

USEPA (U.S. Environmental Protection Agency). 2000. *Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories.* Vol. 2. Risk Assessment and Fish Consumption Limits. 3rd Ed. USEPA 823-B-00-007. Office of Water. Washington, D.C.

USEPA (U.S. Environmental Protection Agency). 2002. *Total Maximum Daily Loads for Toxic Pollutants San Diego Creek and Newport Bay, California*. Technical Support Document, Part D: Selenium. USEPA Region 9.

USEPA (U.S. Environmental Protection Agency). 2004. *Draft Aquatic Life Water Quality Criteria for Selenium – 2004.* USEPA-822-D-04-001, Office of Water. Washington, D.C.

USEPA (U.S. Environmental Protection Agency). 2014. Aquatic Life Ambient Water Quality Criteria for Selenium – Freshwater 2014 (PDF) External Peer Review Draft. May 2014.

USFWS (U. S. Fish and Wildlife Service). 2012. *Evaluation of the Toxicity of Selenium to White and Green Sturgeon.* U.S. Fish and Wildlife Service, Sacramento Fish and Wildlife Office, Environmental Contaminants Division. Sacramento, California. March 2012. 48 pp.

USGS (U.S. Geological Survey). 2001a. *Sedimentation Changes in San Pablo Bay*, 1856-1983, http://sfbay.wr.usgs.gov/sediment/sanpablobay/ Prepared by B. Jaffe, R. Smith, and L. Zink.

USGS (U.S. Geological Survey). 2001b. *Historical Bathymetric Change in Suisun Bay*, 1867-1990, http://sfbay.wr.usgs.gov/sediment/suisunbay/ Prepared by K. Cappiella, C. Malzone, R. Smith, and B. Jaffe.

Van Kirk, R.W. and S.L. Hill. 2007. "Demographic model predicts trout population response to selenium based on individual-level toxicity". *Ecological Modelling,* 206: 407–420.

Wainwright-De La Cruz, S.E. 2010. *Habitat, Diet, and Contaminant Relationships of Surf Scoters Wintering in San Francisco Bay: Implications for Conservation in Urban Estuaries*. Ph.D. Dissertation. Davis (CA): University of California Davis. 215 p.

Wilson, D.S., Zhang, P., He, R., Ota, R. and S.T. Omaye.1997. "Kinetics of selenium incorporation into tissues of female mallard ducks". *Toxicology,* 122: 51–60.

Yee, D., Bemis, B., Hammond, D., Heim, W., Jaffe, B., Rattonetti, A., and S. van Bergen. 2010. *Age Estimates and Pollutant Concentrations of Sediment Cores from San Francisco Bay and Wetlands*. A Technical Report of the Regional Monitoring Program: SFEI Contribution (in preparation). San Francisco Estuary Institute, Oakland, CA. 45pp.

Yee, D. 2012. *Selenium Fractionation and Speciation in Final Effluents of Selected San Francisco Bay Area Municipal Wastewater Treatment Facilities.* Technical Memorandum prepared for Bay Area Clean Water Agencies. April 24th, 2012. http://www.sfei.org/documents/Se-fractionation-and-speciation-final-effluents-selected-san-francisco-bay-area-muni .

Zeug, S.C., Brodsky, A., Kogut, N., Stewart, A.R. and J.E. Merz. 2014. "Ancient fish and recent invaders: white sturgeon *Acipenser transmontanus* diet response to invasive species-mediated changes in a benthic prey assemblage". *Marine Ecology Progress Series*, 514: 163–174.

Page left intentionally blank

APPENDIX A

DRAFT PROPOSED BASIN PLAN AMENDMENT

The following text is to be inserted into Chapter 7.2.

7.2.4 North San Francisco Bay Selenium Total Maximum Daily Load (TMDL)

The following sections establish the TMDL for selenium in North San Francisco Bay segments (North Bay) including the portion of the Sacramento/San Joaquin Delta (within the San Francisco Bay region), Suisun Bay, Carquinez Strait, San Pablo Bay, and Central Bay. The associated numeric targets, allocations, and implementation plan are designed to ensure attainment of selenium water quality standards, including beneficial uses in the North Bay.

7.2.4.1 Problem Statement

This TMDL addresses selenium impairment in the North San Francisco Bay segments. Selenium is an essential and naturally occurring micronutrient, but in high quantities can cause reproductive impairment. Dietary uptake of particulate selenium is the most important exposure pathway for aquatic organisms, especially predators, and some types of food webs bioaccumulate selenium more efficiently than others. In the North Bay, selenium bioaccumulation has been detected only in clam–eating bottom feeders, such as white sturgeon and Sacramento splittail. Sturgeon feed predominantly on benthic organisms, including invasive, non-native clams (i.e., *Potamocorbula amurensis*) that are very efficient selenium bioaccumulators, which makes sturgeon susceptible to bioaccumulation of selenium to toxic levels. This TMDL is intended to ensure protection of the estuarine habitat beneficial uses, and to the extent that other beneficial uses are affected by selenium, the TMDL will also ensure protection of other beneficial uses, specifically, preservation of rare and endangered species, wildlife, and commercial and sport fishing beneficial uses.

7.2.4.2 Numeric Targets

The numeric targets for the North Bay are listed in Table 7.2.4-1. These targets are intended to be protective of all fish species.

Table 7.2.4-1 Numeric Targets for Selenium

Fish Tissue Targets	Water Column Target
8.1 µg/g whole-body dry weight **11.8** µg/g muscle tissue dry weight	**0.5** µg/L (dissolved total Se)

Attainment of either the fish tissue targets or the water column target will be evaluated to assess protection of beneficial uses. The whole-body fish tissue target is the basis for the water column target. Attainment of the fish tissue targets will be evaluated by comparing measured selenium concentrations in fish to whole-body target concentrations, except for sturgeon, which will be compared to the muscle tissue target. Sturgeon are large fish and comparison to the whole-body numeric target is not feasible. Because the water column target is derived from the whole-body fish tissue target, it represents longer-term bioaccumulation in fish and is therefore considered to represent chronic conditions. Use of nonlethal sampling methods, i.e., sampling of tissue plugs, in lieu of muscle tissue sampling for sturgeon, is allowed, if there is documentation that the nonlethal method provides data comparable to muscle tissue sample data.

7.2.4.3 Sources

The main inputs of selenium into the North Bay include contributions from Sacramento and San Joaquin Rivers as Central Valley watershed load (4070 kg/yr), local tributaries (520 kg/yr), atmospheric deposition (<30 kg/yr) discharges from petroleum refineries (571 kg/yr) and municipal and industrial wastewater dischargers (116 kg/yr). While loads from the Sacramento River, local tributaries, and atmospheric deposition represent natural background, the San Joaquin River loads include an anthropogenic source, agricultural drainage, generated by irrigation of seleniferous soils.

7.2.4.4 Total Maximum Daily Load and Allocations

The TMDL for selenium is 5300 kg/year and represents the sum of loads from the existing major sources (Table 7.2.4-2). Because selenium bioaccumulation is a long-term process there is no evidence that selenium bioaccumulation is notably higher at any particular time of year, despite the strong seasonal variability in loads reaching the North Bay.

The TMDL is based on long-term estimates of loads from major sources, therefore the TMDL and allocations are expressed as annual loads.

Load allocations for major source categories are presented in Table 7.2.4-2. Individual wasteload allocations for petroleum refineries and municipal and industrial wastewater dischargers are presented in Table 7.2.4-3 and Table 7.2.4-4.

Table 7.2.4-2 Selenium Load Allocations

Load Category	Load Source	Allocations [kg total Se per year]
Load Allocations	Central Valley Watershed	4070
	Local Tributaries	520
	Atmospheric deposition	<30
Wasteload Allocations	Petroleum Refineries	571
	Municipal Wastewater Dischargers	111
	Industrial Wastewater Dischargers	5
	Total TMDL	***5300***

Total TMDL load differs from column sum due to rounding

Table 7.2.4-3 Individual wasteload allocations for petroleum refineries

Permitted Entity	NPDES Permit	Allocation [kg/yr]
Chevron Products Company	CA0005134	111
Phillips66 *(formerly ConocoPhillips)*	CA0005053	93
Shell Oil Products US	CA0005789	244
Tesoro Refining and Marketing Company	CA0004961	60
Valero Refining Company	CA0005550	63
	Total	***571***

Table 7.2.4-4 Individual wasteload allocations for municipal and industrial dischargers

Permitted Entity	NPDES Permit	Allocation [kg/yr]
Municipal		
City of American Canyon	CA0038768	1.6
City of Benicia	CA0038091	1.1
City of Calistoga	CA0037966	0.3
Central Contra Costa Sanitation District	CA0037648	17.4
Central Marin Sanitation Agency	CA0038628	4.0
Contra Costa Co. Sanitary District No.5	CA0037885	0.1
Delta Diablo Sanitary District	CA0038547	8.1
East Bay Municipal Utility District	CA0037702	30.0
Fairfield-Suisun Sewer District	CA0038024	9.7
Las Gallinas Valley Sanitary District	CA0037851	1.2

Permitted Entity	NPDES Permit	Allocation [kg/yr]
Marin County S.D. No 5	CA0037427	0.5
Mt. View Sanitary District	CA0037770	1.1
Napa Sanitation District	CA0037575	6.7
Novato Sanitary District	CA0037958	2.5
City of Petaluma	CA0037810	3.4
City of Pinole	CA0037796	2.2
Rodeo Sanitary District	CA0037826	0.4
Sausalito-Marin City Sanitary District	CA0038067	1.9
Sewerage Agency of Southern Marin	CA0037711	1.4
Sonoma Valley County Sanitary District	CA0037800	2.1
City of St. Helena	CA0038016	0.4
Treasure Island	CA0037810	0.1
Vallejo Sanitation & Flood Control District	CA0037699	6.7
West County Agency	CA0038539	7.9
Town of Yountville	CA0038121	0.2
Industrial		
Solvay (formerly Rhodia, Inc.)	CA0006165	0.5
USS-Posco Industries	CA0005002	4.5
	Total	***116***

7.2.4.5 Implementation Plan

The intent of this implementation plan is to ensure attainment of selenium water quality standards. Existing selenium concentrations in water column are below the TMDL target. Concentrations in sturgeon have been gradually decreasing since the late 1990s. For these reasons, it is appropriate to base the TMDL on current loading and focus the implementation plan on maintaining current load into the future.

The main goal of the implementation plan is to prevent increases of selenium concentrations in North Bay waters and attain safe levels of selenium in fish, specifically sturgeon. This will be accomplished through:

- performance-based effluent limits for petroleum refineries;
- maintaining control actions to reduce loads from the San Joaquin River watershed; and
- continuation of ambient water quality monitoring in the North Bay and monitoring of flow and selenium concentrations in lower San Joaquin River.

Because loads from the Sacramento River, local tributaries, and atmospheric deposition are representative of natural background, no other implementation actions are necessary.

Petroleum Refineries

Wasteload allocations for the five North Bay petroleum refineries shall be implemented through NPDES permits with performance-based mass limits expressed as kg/day. The mass limit shall be calculated as the 95^{th} percentile of the daily loads based on representative effluent data collected during the period of 2000 through 2012. Establishing mass limits as the 95^{th} percentile of daily loads is consistent with the calculation of annual loads and the wasteload allocations. Petroleum refineries shall report their average annual load once per permit term. Compliance with the mass limits shall be determined on a monthly basis. The monthly average of daily loads should not exceed the mass limit. Permits shall also require the petroleum refineries to conduct or cause to be conducted monitoring to demonstrate attainment of the numeric targets.

Municipal and industrial wastewater dischargers

NPDES permits for municipal and industrial wastewater dischargers are not required to have numeric effluent limits for selenium because these discharges have an insignificant impact on North Bay water quality and no further selenium reductions are required to ensure attainment of the TMDL. To ensure protection of North Bay water quality, municipal and industrial wastewater dischargers will be required once per permit term to verify that selenium loading continues to be equal to or less than the wasteload allocations identified in Table 7.2.4-4. Permits shall also require the dischargers to conduct or cause to be conducted monitoring to ensure the numeric targets are being attained.

Central Valley Watershed (San Joaquin River)

Selenium loads in the Sacramento River watershed are from naturally occurring sources and are expected to remain at current levels or less. The San Joaquin River system is an exception because it conveys selenium-enriched agricultural drainage and runoff to the Delta and the North Bay. Attainment of the Central Valley watershed load allocation relies on continued efforts to manage and reduce discharge of agricultural subsurface drainage in the San Joaquin River watershed. The Central Valley Regional Water Quality Control Board has established three TMDLs for selenium in San Joaquin River system water bodies receiving agricultural drainage. These TMDLs are implemented through the Grasslands Bypass Project, and implementation actions have gradually reduced the load of selenium discharged to these water bodies. Full attainment of the TMDLs is expected by 2019. Changes to the State Water or Central Valley Projects' operations, other upstream diversions or flow modifications cause increases of selenium loading into the North Bay, specifically from increased flows from the San Joaquin River, but these increases are not expected to be significant.

Monitoring

Monitoring to demonstrate attainment of the TMDL targets shall be conducted by maintaining discharger-funded RMP monitoring of selenium in fish and water at a spatial scale and frequency to determine whether concentrations in fish, specifically sturgeon, remain low and water column and fish tissue targets are met.

Monitoring of loads to demonstrate that there are no load increases above the wasteload allocations shall be conducted by petroleum refineries and municipal and industrial wastewater dischargers.

The Water Board will work with the State Water Board and Central Valley Water Board through their planning and regulatory processes to ensure that monitoring is conducted to evaluate changes in selenium concentrations and loads from the Central Valley Watershed and San Joaquin River and to ensure that any increases in selenium upstream are addressed through the State Water Board's or Central Valley Water Board's regulatory processes.