Conceptual Model for Selenium

Newport Bay Watershed

INTERIM REPORT

May 15, 2006

Prepared for the
Nitrogen and Selenium Management Program (NSMP) Working Group

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The thoughtful review and comment of NSMP Working Group is gratefully acknowledged.

This report fulfils the requirements under Task 1.1 of the NSMP Year 1 Work Plan, and fits within the overall NSMP framework as shown below:

NSMP Task - Document Key
Task 1 Complementary Monitoring
➲ **Task 1.1 Conceptual Models for Nitrogen and Selenium**
Task 1.2 Sources and Loads of Nitrogen and Selenium
Task 1.3 Bioavailability and Impacts of Selenium
Task 1.4 Impacts of Nitrogen
Task 1.5 Lines of Evidence Approach for BMP Implementation
Task 1.6 Selenium Speciation Method(s)
Task 1.7 Support for BMP and Trading Tasks
Task 2 Develop and Evaluate BMPs/Treatment Technologies
Task 3 Develop Offset, Trading or Mitigation Program
Task 4 Evaluate Nutrient TMDL
Task 5 Develop Site-Specific Objective (SSO) for Selenium
Task 6 Management and Communication

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Acronyms and Symbols used in this Report

μg/g: microgram per gram

μg/L: microgram per liter

Ag: agricultural

ATSDR: Agency for Toxic Substances and Disease Registry

BAF: bioaccumulation factor

bgs: below ground surface

BMP: best management practice

BSAF: biota-to-sediment accumulation factor

The Department: California Department of Transportation

diss: dissolved

DynBaM: Dynamic Multi-pathway Bioaccumulation Model

dw: dry weight

EDTA: ethylenediamine tetra-acetic acid

GSH-PX: glutathione peroxidase

GW: groundwater

GWTF: Ground Water Treatment Facility

IRWD: Irvine Ranch Water District

LA: load allocation

lbs/day: pounds per day

lbs/yr: pounds per year

LOEC: lowest observed effect concentration

LWA: Larry Walker Associates

MCAS: Marine Corps Air Station

mg/kg: milligram per kilogram

MOS: Margin of Safety

NAS-NRC: National Academy of Science-National Research Council

NPDES: National Pollutant Discharge Elimination System

NRC: National Research Council

OCRDMD: Orange County Resources and Development Management Department

pH: potential of hydrogen (negative logarithm of the hydrogen ion concentration)

Se: selenium

sed: sediment

SLD: San Luis Drain

SPM: suspended particulate matter

TIE: toxicity identification evaluation

TMDL: total maximum daily load

USDI: United States Department of the Interior

USEPA: United States Environmental Protection Agency

WLA: wasteload allocation

1. 1. INTRODUCTION

On December 20, 2004, the Santa Ana Regional Water Quality Control Board (Regional Board) issued Order No. R8-2004-0021 (NPDES No. CAG998002) (Order), which specifies waste discharge requirements for short-term (i.e., one year or less) groundwater-related discharges and for *de minimus* discharges within the San Diego Creek/Newport Bay watershed (hereafter referred to as Newport Bay watershed or watershed). The Order was issued due to the concern that the groundwater-related discharges in the watershed have the potential to adversely affect surface waters and would likely not comply with established Total Maximum Daily Loads (TMDLs) for the watershed. Due principally to the presence of nitrates and selenium, and potentially other pollutants of TMDL concern, the Regional Board found that it would be inappropriate to regulate these types of groundwater-related discharges (i.e., those associated with well installation, development, test pumping and purging; aquifer testing wastes; construction dewatering; and wastes from subterranean seepage) within the Newport Bay watershed as *de minimus* discharges.

The Order incorporates an alternative compliance approach that requires either (a) compliance with an average monthly selenium concentration limit of 4 μg/L and a daily maximum selenium concentration limit of 8 μg/L, or (b) participation in a Working Group to develop and implement a comprehensive Work Plan to address selenium and nitrate discharges in the watershed over the 5-year permit term.

The Order establishes certain tasks that must be completed by the Working Group through the implementation of the Work Plan, including the filling of the data gaps regarding selenium and nutrients to understand the extent of the ecosystem impacts, examining Best Management Practices (BMPs) and treatment technologies that can reasonably be applied throughout the watershed to reduce the inputs of selenium and nitrates, building upon this knowledge to develop a management program (i.e., a trading, offset, or mitigation program) for selenium and nutrients in the watershed, and, if necessary, developing a site-specific objective for selenium for the Newport Bay watershed.

A Working Group has been formed, and has developed a detailed Work Plan that incorporates the commitments and concepts of the Order. That Work Plan was developed and submitted to the Regional Board on June 20, 2005. RBF, CH2M HILL, and Larry Walker and Associates (LWA) were contracted by the Working Group to implement the Work Plan. Two of the primary objectives of this contract are to:

- Support compliance with Order No. R8-2004-0021 by implementing the detailed Nitrogen and Selenium Management Program Work Plan approved by the Regional Board;
- Develop a comprehensive understanding of, and management plan for, nutrients and selenium discharges to surface waters within the Newport Bay watershed that result from groundwater-related inflows.

This report summarizes the conceptual model for selenium movement within the Newport Bay watershed. The model includes general information on selenium sources, fate and transport of selenium in the watershed, preliminary summaries of existing concentrations of selenium, an approach for developing watershed-specific bioaccumulation models, and a preliminary summary of potential effects of selenium on fish and wildlife. This document represents the first of three tasks that build on each other. The conceptual model primarily contains the graphical depiction of the selenium movement in the Newport Bay watershed (Section 2.0), with preliminary information on sources as well as concentrations in the watershed. As part of a separate task, a current analysis of the sources and loads, including calculations of loads using all available data, will be conducted. Through a third task to identify data gaps, data required to develop site-specific values for each conceptual model component (e.g., partitioning coefficients and bioaccumulation models) will be identified and any gaps reported. These three documents provide support for development of a field sampling plan to fill the data gaps.

As a first step in understanding selenium in the watershed, a summary of selenium biogeochemistry in aquatic systems, as well as selenium issues specific to the Newport Bay watershed, are presented below. Additionally, the conceptual model underlying the Toxics TMDL section for selenium developed for the watershed by the U.S. Environmental Protection Agency (USEPA, 2002) is summarized. (Note, however, that there currently is no "stand alone" Selenium TMDL – selenium is included as a section of the overall Toxics TMDL for Newport Bay watershed promulgated by the USEPA in 2002. The Regional Board is currently working on the development of an implementation plan and will adopt a Basin Plan Amendment for a selenium TMDL.)

1.1. SELENIUM BIOGEOCHEMISTRY

Selenium has been extensively studied in aquatic systems since the mid-1980s, when observed toxic impacts to birds nesting at the Kesterson Reservoir (Merced County, California) were first associated with elevated selenium concentrations. Recently, several reviews and assessments of selenium have been published, including those by Hamilton (2004), Ohlendorf (2003), the Agency for Toxic Substances and Disease Registry (ATSDR, 2003), Luoma and Presser (2000), Eisler (2000), Frankenberger and Engberg (1998), U.S. Department of the Interior (USDI, 1998), and Frankenberger and Benson (1994). In addition to these recent reports, Lemly and Smith (1987) provide a detailed description of selenium cycling in aquatic systems. A brief summary of the salient features of general selenium biogeochemistry is provided below.

Selenium is a naturally occurring element found in rocks and soils. Selenium occurs in several forms, including multiple oxidation states, which vary depending on ambient conditions (such as pH, Eh [oxidation/reduction potential], and microbial activity), as well as the environmental medium (such as water, sediment, or biological tissue). Biologically significant oxidation states include selenide (Se^{2-}), elemental selenium (Se^{0}), selenite (Se^{4+}), and selenate (Se^{6+}).

The behavior of selenium in the environment is largely influenced by its oxidation state as well as physical factors such as geology, climate, and hydrology. Selenium is often more abundant in environmental media in areas with Upper Cretaceous marine sedimentary rocks and other formations naturally high in selenium (USDI, 1998). Climate also affects selenium distribution, because it behaves differently in arid climates than in humid or wet climates. In areas that have a local geologic source of selenium (as discussed above), concentrations and the potential for toxic effects generally increase as aridity increases. Hydrology can increase selenium contamination by acting as a transporting agent, and certain receiving waterbodies may become sinks for the mobilized selenium. Selenium is transported via rivers, streams, creeks, groundwater, and irrigation drainage water. Terminal waterbodies may become contaminated due to evaporative enrichment and sequestering over several seasons of runoff. These physical factors influence the fate and transport of selenium in various environmental media.

As outlined by Lemly and Smith (1987), dissolved selenium entering an aquatic system can 1) be absorbed or ingested by organisms, 2) bind or complex with particulate matter, or 3) remain free in solution. Although most selenium is either taken up by organisms or bound to particulate matter over time, selenium does not remain constant in the system. Instead, biological, chemical and physical processes move selenium through the system such that selenium stored in sediments can be cycled back into the biota and remain at elevated concentrations even when inputs of dissolved selenium are reduced or stopped.

The processes involved in the immobilization and mobilization of selenium in aquatic ecosystems are detailed in Lemly and Smith (1987), and are depicted in **Figures 1** and **2**. Briefly, waterborne selenium (selenite, selenate, and organic selenium) is sequestered into sediment through chemical and microbial reduction, followed by adsorption to clay and organic carbon and co-precipitation or settling (**Figure** 1). Additionally, selenium in animal and plant tissues is deposited as detritus and is consolidated over time through the process of sedimentation. Within the sediment, further chemical and microbial reduction of sequestered selenium results in insoluble organic, mineral, elemental, or adsorbed selenium.

However, as previously indicated, selenium is usually not permanently sequestered in sediment. Selenium is mobilized from sediment through oxidation and methylation processes and through direct uptake by plants and bottom-dwelling organisms (**Figure 2**). The operative processes include oxidation and methylation of inorganic and organic selenium by roots and microorganisms, and oxidation of sediments by plant photosynthesis. Additionally, burrowing of benthic invertebrates and foraging of fish and wildlife result in the biological mixing and oxidation of sediments. Water circulation and mixing (from physical perturbations such as currents, wind, stratification, precipitation, and upwelling) and associated oxidation also serve to mobilize selenium. However, it is the uptake of selenium by rooted plants and by bottom-dwelling invertebrates and detritus-feeding fish and wildlife that contribute most to the mobilization of selenium.

The fate and transport processes that are most important to the Newport Bay watershed are outlined in Section 2.2.

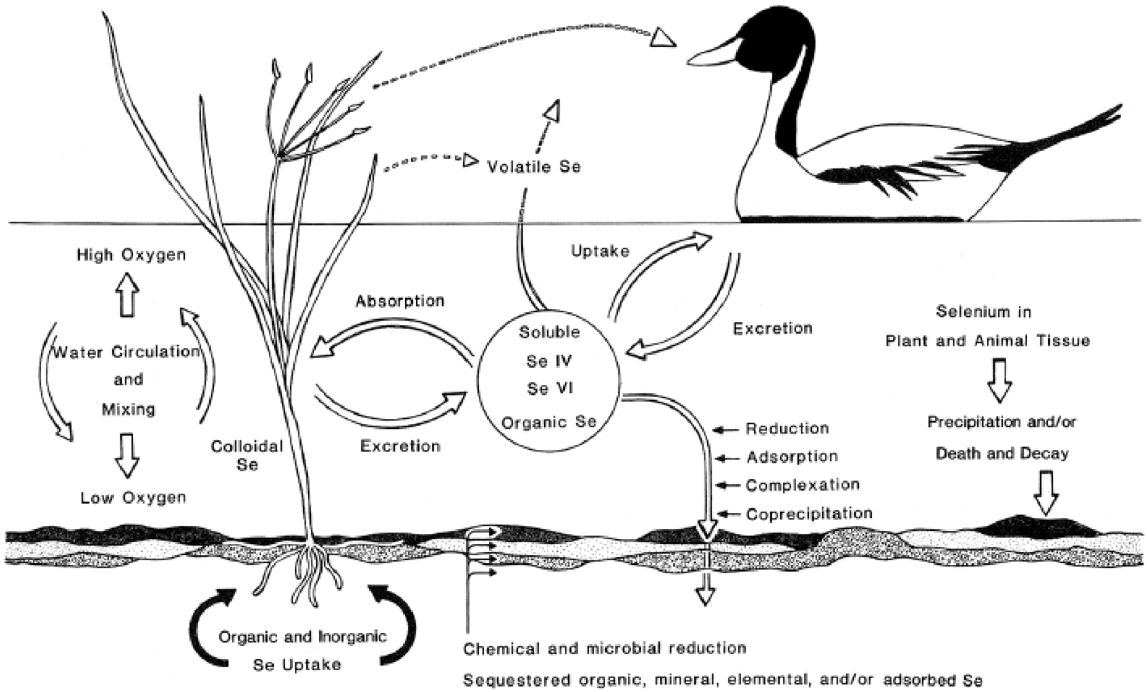


Figure 1: Selenium Immobilization Processes in an Aquatic Ecosystem (Source: Lemly and Smith, 1987)

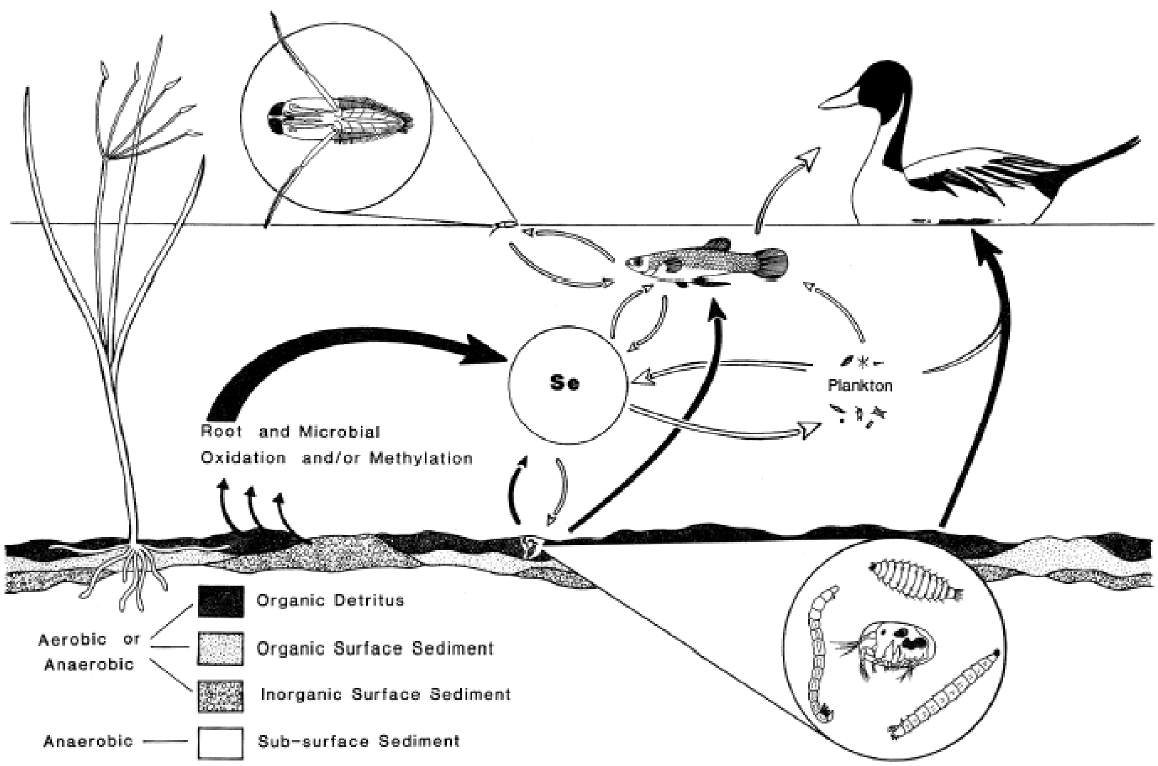


Figure 2: Selenium Mobilization Processes in an Aquatic Ecosystem (Source: Lemly and Smith, 1987)

1.2. SELENIUM ISSUES IN THE NEWPORT BAY WATERSHED

The Newport Bay watershed consists of about 154 square miles, and is located in Orange County in the southwest corner of the Santa Ana River Basin (USEPA, 2002). The watershed is bounded by mountains on three sides. The runoff from these mountains drains across the Tustin Plain and enters Upper Newport Bay via San Diego Creek, which is the largest contributor (95 percent) of freshwater flow into Upper Newport Bay (USEPA, 2002). Due to the semi-arid climate of the region, selenium may be readily mobilized and concentrated by weathering and evaporation in the process of soil formation and alluvial fan deposition. Additionally, the area is heavily developed with industrial, residential, and agricultural land uses, though it was a large terminal marsh, known as the "Swamp of the Frogs," prior to the 1930s. The draining of these historic wetlands and subsequent channelization related to the land uses has resulted in the mobilization of selenium from the former wetland soils (Meixner et al., 2004). As outlined in the Newport Bay Toxics TMDL development (USEPA, 2002), selenium issues are of special concern in the Newport Bay watershed because:

1. Dissolved selenium in San Diego Creek and its tributaries has been measured at concentrations that exceed chronic, and in some cases acute, freshwater toxicity criteria. Exceedances of the saltwater toxicity criteria have not been observed in Newport Bay.

2. Although measured mussel and fish tissue concentrations in the watershed are below levels of concern for human consumption (20 mg/kg wet weight), they are within the range of concentrations of concern for potential toxicological and reproductive effects to wildlife (4-12 mg/kg dry weight). Additionally, measurements of selenium in small whole fish collected from San Diego Creek under the Toxic Substances Monitoring Program indicate an increasing trend from 1983 to 2000. A similar trend has not been observed in Newport Bay, though three species of forage fish (Topsmelt, Arrow goby, and California killifish) recently caught in the uppermost portion of Upper Newport Bay were found to have tissue concentrations that are within the range of concentrations of concern for potential toxicological and reproductive effects in fish and wildlife (Allen et al., 2004).

Further information specific to available abiotic and biotic data collected in the Newport Bay watershed, as well as potential effects data is presented in Sections 2.3 and 2.4, respectively. It is also important to note that systems vary in their selenium cycling (e.g., speciation, sequestration, mobilization, and bioaccumulation) and ecology (e.g., typical diet and food mass) such that effects observed in one ecosystem may not occur in another, despite similar selenium concentrations in surface water, sediment, or biota.

1.3. TMDL SUMMARY

The following summary of the Toxics TMDL (USEPA, 2002) provides a basis for understanding the conceptual model used in the TMDL development. As noted in Section 1, the Regional Board has proposed separating the Toxics TMDL into five distinct TMDLs (i.e., Basin Plan Amendments). One of these would include a specific TMDL and implementation plan for selenium.

Total maximum daily loads for selenium were developed for San Diego Creek and Newport Bay by the USEPA under the Newport Bay Toxics TMDL (USEPA, 2002). The purpose of the document was to describe TMDLs established for several toxic pollutants to "help protect and restore the water quality of Newport Bay, San Diego Creek, and their tributaries"(USEPA, 2002). As defined in the report, "a TMDL identifies the maximum amount of a pollutant that may be discharged to a water body without causing exceedances of water quality standards and impairment of the uses made of these waters." As part of the TMDL development, numeric targets for selenium that were expected to protect and thereby restore beneficial uses in freshwater and saltwater were selected (i.e., the California Toxics Rule chronic freshwater and saltwater criteria and the National Toxics Rule acute freshwater criterion), and the sources of selenium in the watershed were identified. Using these data, the loading capacities of the major waterbodies were calculated and TMDLs were based on these loading capacities.

For San Diego Creek and other freshwater sources, the selected numeric targets (or toxicity thresholds) consist of an acute (20 µg/L) and chronic (5 µg/L) criterion for total selenium. In the saltwater habitats of Newport Bay, a target of 71 µg/L for dissolved selenium (using a <0.45 µm filter) was selected. Sources of selenium were determined to be from both point (nurseries, groundwater cleanup, groundwater dewatering, and urban runoff) and non-point (atmospheric deposition, open space and hillside runoff, agricultural runoff, and groundwater) sources. (Note: urban runoff appears to be considered a point source and refers to the water that flows from the storm drain system to San Diego Creek.) Of the sources identified, groundwater seepage, treated groundwater discharges, and groundwater dewatering discharges were found to be significant and constant sources. In contrast, urban runoff and atmospheric deposition did not contribute significantly to selenium in the system. Nursery runoff was found to be a potential source during rain events, and there was evidence that runoff from open space, hillsides, and agricultural lands may be significant during rain events as well.

The TMDL was set equal to the loading capacity (in pounds per year) for each waterbody. Thus, wasteload allocations (WLAs) for point sources and load allocations (LAs) for non-point sources were determined for this TMDL. Because there are distinct dry and wet seasons in the Newport Bay watershed, seasonal flows and pollutant loads are important to selenium contributions. Therefore, flow-based allocations were developed to achieve the calculated TMDL under four flow tiers (base, small, medium, and large flows). These allocations are presented in **Table 1**. The guidelines associated with these allocations, though not described here, are detailed in USEPA (2002).

Table 1: Selenium Allocations for San Diego Creek Watershed

Source	**Loading Capacity (lbs/year)**					**Current Load[b]**	**Estimated Reductions**
	Tier 1	**Tier 2**	**Tier 3**	**Tier 4**	**Annual Total[a]**		
WLA							
MCAS Tustin	1.6	2	1.8	7.9	13.3		

Table 1: Selenium Allocations for San Diego Creek Watershed

Source	Loading Capacity (lbs/year)					Current Load[b]	Estimated Reductions
	Tier 1	Tier 2	Tier 3	Tier 4	Annual Total[a]		
GW Clean up	6.2	7.8	7.5	36.9	58.4		
GWTF	3.1	3.9	4	21.1	32.1		
GW Dewatering	3.9	4.9	4.5	21.1	34.4		
Future GW Facilities	0.4	0.5	0.5	2.6	4		
Stormwater Permit	0.4	1	1	5.3	7.7		
WLA Subtotal	15.6	20.1	19.3	94.9	149.9		
LA							
All Nurseries	3.1	3.9	4	21.1	32.1		
Agricultural Runoff	5.4	7.3	8	44.8	65.5		
Unidentified Sources[c]	53.4	66.4	69.1	366.2	555.1		
LA Subtotal	61.9	77.6	81.1	432.1	652.7		
Total Allocations	77.5	97.7	100.4	527	802.6	2443	67%
MOS					89.13		
Total TMDL					891.4		

Notes

Source: USEPA (2002)

[a] sum of loading capacity for San Diego Creek only (based on 5 µg/L applied to all flow tiers)

[b] current load based on IRWD Se data (1998-99) and corresponding OCRDMD flow records

[c] undefined sources include open space and hillside runoff, shallow GW, and saltwater Se.

GW = groundwater

GWTF = California Department of Transportation Ground Water Treatment Facility

LA = load allocations

MCAS = Marine Corps Air Station

MOS = margin of safety

Tier 1 = base flow (0-20 cubic feet per second [cfs])

Tier 2 = small flows (21-181 cfs)

Tier 3 = medium flows (182-814 cfs)

Tier 4 = large flows (>814 cfs)

TMDL = total maximum daily load

WLA = wasteload allocations

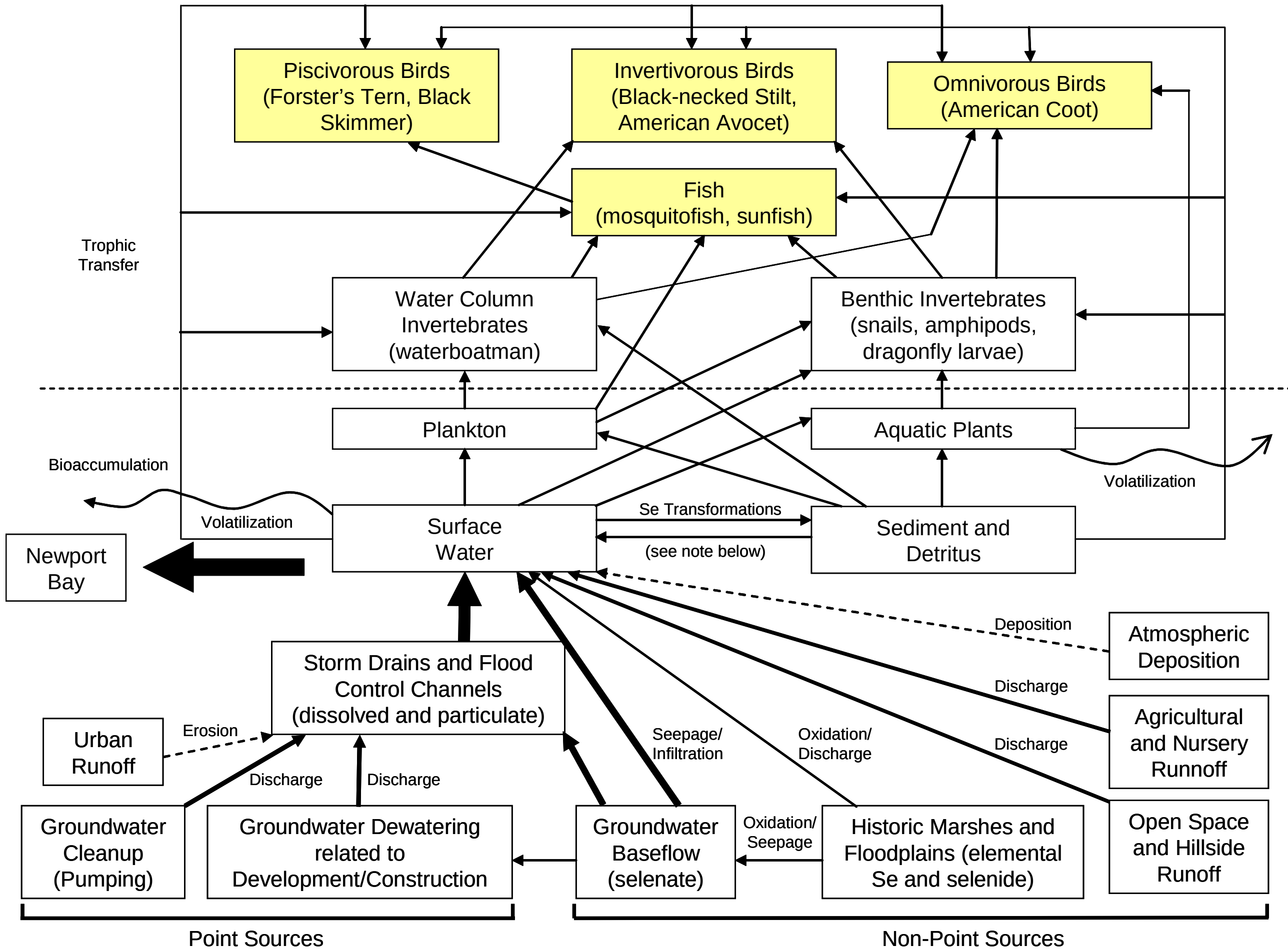
2. 2. CONCEPTUAL MODEL

Development of a conceptual model that describes the movement of selenium within the Newport Bay watershed is essential in achieving a comprehensive understanding of, and creating a management plan for, selenium discharges to surface waters within this watershed. This conceptual model will determine what data are necessary to collect (i.e., it will aid in identifying gaps in existing data), provide a meaningful framework in which the data can be analyzed, result in the ability to answer specific questions, and ultimately lead to a basis to make sound management decisions. (Note: the data gaps will be described in a separate report.)

An explicit conceptual model for selenium has been developed for the San Francisco Bay-Delta Estuary by the U.S. Geological Survey (Luoma and Presser, 2000). That model used existing knowledge of biogeochemical reactions of selenium (e.g., speciation, partitioning between dissolved and particulate forms, and bivalve assimilation efficiency) and site-specific data on clams and bottom-feeding fish and birds to model the fate and effects of selenium under different load scenarios from the San Joaquin Valley. This model was identified in the approved Work Plan as a suitable basis for development of the conceptual model for the Newport Bay watershed. Therefore, the Luoma and Presser conceptual model was reviewed and adapted, as possible, to the Newport Bay watershed. Because of the differing habitats of the San Diego Creek watershed and Newport Bay, separate conceptual models were developed for each. These conceptual models are presented in **Figures 3** and **4**, respectively.

Selenium enters the San Diego Creek watershed via many sources, with groundwater sources (both point and non-point) accounting for most of the selenium discharge to surface waters (**Figure 3**). Once in surface water (dissolved and particulate), selenium may alternate between immobilization in sediments and mobilization from sediments through processes depicted in **Figures 1** and **2**. Selenium in surface water and sediment/detritus moves into the biota in the watershed via bioaccumulation into plankton and aquatic plants, and subsequent trophic transfer to invertebrates (benthic and water column), fish, and aquatic birds. Direct ingestion of surface water and sediment also represents a potential pathway for accumulation of selenium in invertebrates, fish, and aquatic birds. This differs from the San Francisco Bay-Delta Estuary model in that exposure and effects to receptors in the river system upstream of the Bay-Delta were not evaluated. In contrast, the impacts of selenium loads on the freshwater system within the San Diego Creek watershed will be analyzed.

San Diego Creek is the primary source of selenium to Newport Bay. Primary release mechanisms include surface water inflow, bedload sediment inflow, and suspended sediment discharge. Once in sediment and surface water, the immobilization and mobilization processes depicted in **Figures 1** and **2** drive the cycling of selenium in the bay. Bioaccumulation and trophic transfer of selenium to biota are similar to that described for the San Diego Creek watershed, although benthic invertebrates are likely to be the primary source for trophic transfer. This is supported by Luoma and Presser (2000), in which bivalves (a benthic organism) were determined to be representative of the primary exposure pathway to aquatic birds. It should also be noted that site-specific



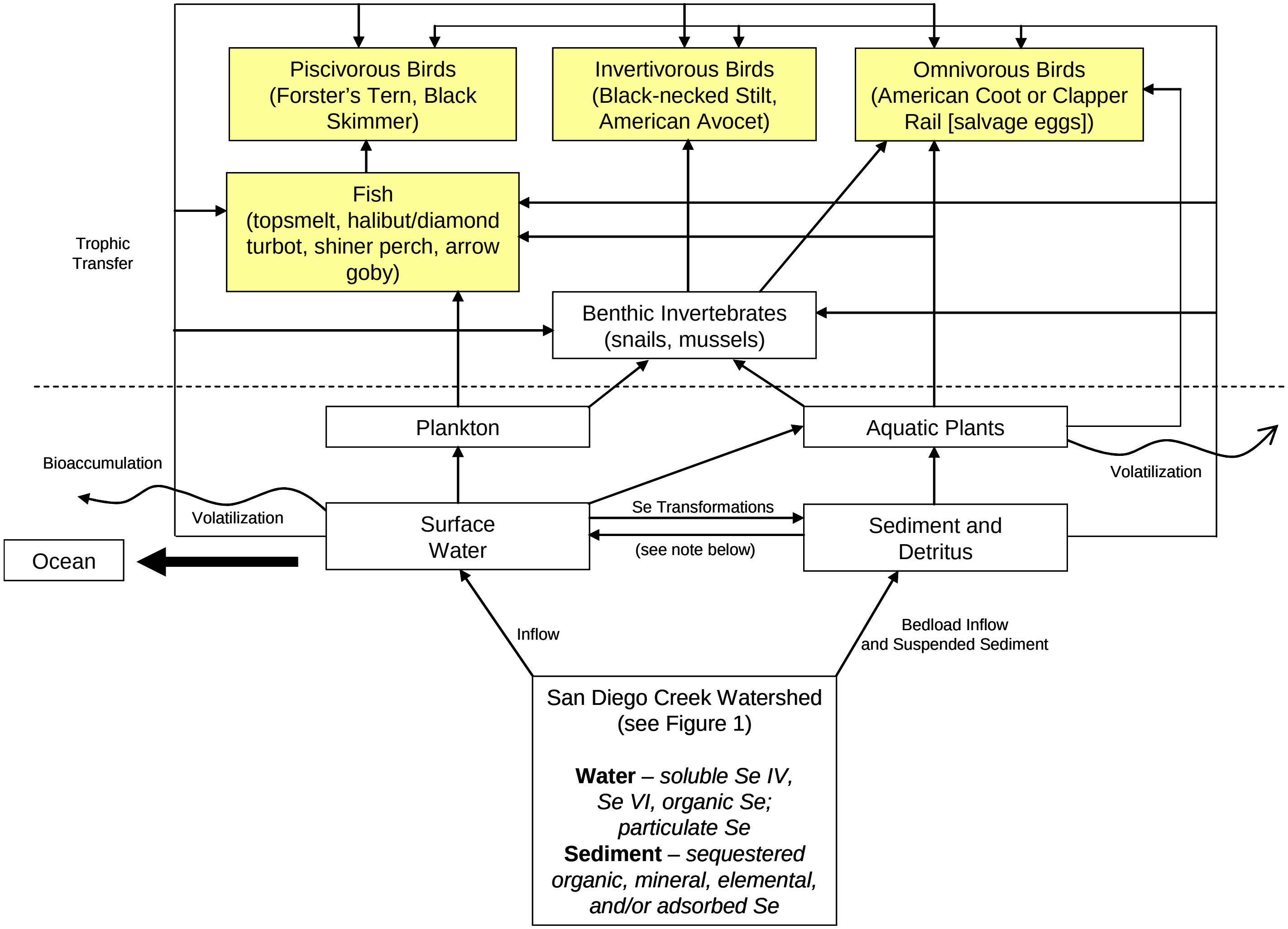
Notes:

Shaded Boxes = assessment species for effects

Weight of line from source indicates significance of contribution of selenium to the watershed (e.g., dotted line indicates insignificant contribution, whereas a heavy line indicates significant contribution).

Figures 1 and 2 provide details on selenium transformations between sediment and surface water (e.g., bacterial processes), as well as details on loss due to volatilization.

Figure 3: Conceptual Model, Exposure Pathways, and Food-Web Relationships for Freshwater Creek and Wetland Habitat within the Newport Bay Watershed



Notes:

Shaded Boxes = assessment species for effects

Figures 1 and 2 provide details on selenium transformations between sediment and surface water (e.g., bacterial processes), as well as details on loss due to volatilization.

Figure 4: Conceptual Model, Exposure Pathways, and Food-Web Relationships for Habitat within Newport Bay

bioaccumulation to topsmelt is part of the Newport Bay conceptual model (**Figure 4**). This is a water-column/pelagic species that integrates water column exposure. For these reasons, water column invertebrates are not included in the Newport Bay conceptual model (**Figure 4**). Assessment species for both models are fish and aquatic birds.

Although the Newport Bay watershed conceptual models were developed using the Luoma and Presser (2000) model as a guide, there are some basic differences between the two models. As with our model, Luoma and Presser (2000) determined loads for major selenium sources (agricultural drains, oil refineries, and the two major rivers, Sacramento and San Joaquin) to the San Francisco Bay-Delta Estuary. However, it does not model exposure or evaluate effects in these freshwater reaches of the system. Instead, the focus is on modeling exposure to Bay-Delta aquatic birds. Therefore, bioaccumulation is determined for a single food item (clams) assumed to be representative of the major dietary exposure pathway to aquatic birds utilizing the area. In contrast, bioaccumulation models for multiple food items in both the freshwater habitats of the San Diego Creek watershed and the saltwater habitats of Newport Bay are required for development of adequate exposure models.

As with the Luoma and Presser model, describing and quantifying selenium in each compartment of the model is essential for its future use as a predictor of the fate of selenium under differing load scenarios within the watershed. Therefore, the following sections include details and, as possible, quantification of relevant compartments of the model including the sources and loading, fate and transport of selenium within the watershed (including partitioning, transformation, and distribution coefficients for exposure media), and existing data on concentrations of selenium in the watershed. Additionally, an approach (including a description of available data) for developing bioaccumulation models for the San Diego Creek watershed and for Newport Bay is discussed.

2.1. SOURCES

Several sources that contribute to selenium levels in the Newport Bay watershed have been identified (Hibbs and Lee, 2000; USEPA, 2002; Meixner et al., 2004). To understand the sources of selenium in the system, it is important to understand the changing land uses of the region and their impact on the mobilization of selenium. The region was historically dominated by a large wetland/marsh area known as "La Cienega de las Ranas" or the "Swamp of the Frogs" and was primarily used for sheep and cattle grazing with some limited provision crops (Trimble, 1998). After 1900, irrigated commercial crops and orchards became important in the area and as a result, portions of the swamp were drained and planted. By 1915, the open channels had been expanded to drain several hundred acres and Bee Canyon, Agua Chinon, and Borrego Canyon washes were channelized and extended to San Diego Creek (Trimble 1998). In 1920, the Santa Ana River was diverted westward from Lower Newport Bay directly to the ocean. Post World War II, urbanization of the watershed expanded rapidly; former agricultural channels were converted to flood control channels and by the 1960s Peters Canyon Wash and the lower portion of San Diego Creek were widened and extended to carry storm flows to Upper Newport Bay (Trimble 1998)

The historic swamp was a naturally-reducing anoxic environment that acted as a sink for selenium in the region. Construction of agricultural drainage channels to carry water from the Swamp of the Frogs resulted in a local lowering of the water table and created a shallow perched groundwater aquifer that contains more oxygen than the groundwater did prior to the draining. These oxidizing soil conditions are considered the primary cause of releases of historically stored selenium, primarily in the selenate form (Hibbs and Lee, 2000: Meixner et al., 2004). Groundwater flow paths were also changed as groundwater preferentially moved to newly-created discharge points (i.e., the agriculture ditches). Local oxygen-rich rainfall now percolates through the former marsh soils, oxidizing and mobilizing selenium and flushing it from the vadose zone soils into the shallow aquifer.

Selenium-enriched groundwater flows into the surface water channels in areas of springs and gaining reaches of the streams. Groundwater enters the surface water through the hyporheic zone as seeps along the sides of unlined channels, through cracks and weepholes in concrete-lined channels, through leaky storm drains (Hibbs, 2004), by passive dewatering systems (e.g., french drains and subdrains) in existing developments, and by point sources such as construction dewatering, permanent dewatering for roads and other structures, and groundwater remediation.

Selenium contributions to the San Diego Creek watershed include both point and non-point sources. Point sources are those sources that discharge a pollutant through discrete pipes or other conveyances (USEPA, 2002). These sources are regulated under the National Pollutant Discharge Elimination System (NPDES) permit program. Point sources for the Newport Bay watershed include pumping of groundwater during groundwater cleanup efforts, groundwater dewatering (i.e., removal of groundwater seepage) associated with construction projects (i.e. short-term discharges) and below grade structures (i.e. long-term discharges), and urban runoff.

Non-point sources are generally those that discharge pollutants via diffuse runoff from land, primarily driven by rainfall events (USEPA, 2002). Non-point sources of selenium in the Newport Bay watershed include atmospheric deposition, runoff from open space and hillsides within the watershed, unpermitted agricultural and nursery runoff, and groundwater seepage into San Diego Creek and other tributaries of the watershed (i.e., baseflow).

Of these sources, groundwater appears to be the greatest contributor of selenium to the watershed. For example, Meixner et al. (2004) report that 96 percent of the selenium load entering Newport Bay is from groundwater sources in the watershed. A detailed description of the selenium sources and estimated contribution of each to selenium loads in the watershed will be completed as a separate task solely devoted to further investigation of sources and loads.

2.2. FATE AND TRANSPORT OF SELENIUM IN THE SAN DIEGO CREEK WATERSHED AND NEWPORT BAY

As previously discussed (Section 1.1), the behavior of selenium in the environment is influenced by the speciation of selenium (oxidation state) and by physical factors (e.g., geology, climate, and hydrology). A first step in determining the fate and transport of selenium is an understanding of the hydraulic connections and conveyances of selenium within the Newport Bay watershed. These aspects of the hydrology of the watershed have been discussed in several studies of the system, including the more recent Meixner et al. (2004) study, and are summarized in Section 2.2.1 below. Next, the partitioning and transformation of selenium within various ecological compartments (waterborne, particulate matter and sediment, and biota) are briefly summarized from the available literature (e.g., Lemly and Smith, 1987; Luoma and Presser, 2000). The distribution coefficients (Kds) for these compartments are also generally discussed, with site-specific values provided as available. Because Kds are very specific to site conditions, particularly for uptake to biota, site-specific Kd values will ultimately be determined for each compartment and will be added to the following sections at a later time.

2.2.1. Hydraulic Connections and Conveyance of Selenium within the San Diego Creek Watershed and to Newport Bay

Basic information on the hydraulic connections within the Newport Bay watershed has been presented in many sources. The following description of the hydraulic connections and conveyance of selenium in the Newport Bay watershed is a summary of details provided in Meixner et al. (2004). The watershed comprises the low-lying Tustin Plain bordered by Loma Ridge, the Santa Ana Mountains, and the San Joaquin Hills. Peters Canyon Wash and San Diego Creek, as well as several tributaries, drain the watershed southwestward toward the Pacific Ocean (**Figure 5**). Most of the flow from the drainage enters Newport Bay via San Diego Creek, and a smaller portion enters through the Santa Ana-Delhi Channel and other smaller channels and storm drains that discharge directly to the Bay (e.g., Costa Mesa Channel, Big Canyon Wash). There are two main aquifers under the watershed, a shallow aquifer within the upper 150 feet of strata and a regional aquifer that extends from 150 feet below ground surface (bgs) to greater than 1,500 feet bgs. There is evidence that the shallow and deep aquifers are not hydraulically connected; however, the shallow aquifer has connections to surface water, and is involved in the transport of selenium in the watershed. Much of the shallow aquifer flow discharges into surface channels within the watershed. Hibbs and Lee (2000) report gaining conditions in several tributaries in the watershed, as does the County of Orange (2005) for Warner Channel. The results of these studies confirm significant groundwater contribution to surface water. However, it should be noted that groundwater contributions may vary over time and season (e.g., groundwater contribution may be higher following wet conditions than during drought periods).

Figure 5: Newport Bay Watershed

As described in Section 2.1 and detailed in Meixner et al. (2004), land use changes in the region since the 1930s have resulted in altered surface and subsurface flows within the watershed. Channel incision over this period is estimated to have contributed two-thirds of the total sediment load to Newport Bay. Although selenium concentrations in this sediment were not available, channel incision may have been an erosional source of selenium to the watershed. Selenium has been mobilized through oxidation of soils in the former marsh area and flushed from the vadose zone into the shallow groundwater aquifer. Once selenium enters surface water bodies it becomes available for uptake into biota. Selenium, therefore, may be found in the watershed in different states – as dissolved waterborne selenium (groundwater and surface water), as bedload or suspended sediment and other particulate matter (e.g., suspended inorganic material, sediments, detritus), and in biota.

2.2.2. Waterborne Selenium

Waterborne selenium in the Newport Bay watershed is found in both groundwater and surface water.

Partitioning

Because selenium is primarily sequestered in sediment and/or particulate matter, knowledge of the partitioning between this bound sediment/particulate matter and water is important for an understanding of selenium cycling in a system. In the Newport Bay watershed, selenium in groundwater is a major source of selenium to the surface water and subsequently the sediments of the watershed. This selenium is mobilized through oxidation of exposed soils in the lowering shallow aquifer. Therefore, partitioning between soil and groundwater is also important.

Transformation

In general, relatively small amounts of selenium are found dissolved in water (Furr et al., 1979; Nriagu and Wong, 1983; Lemly, 1985a; Ohlendorf, 1989). The most common forms of selenium in water are selenic and selenious acids. Soluble selenate salts of selenic acid are expected to occur in alkaline waters. Sodium selenate is highly mobile due to its high solubility and inability to adsorb onto soil particles. Bender et al. (1991) found that bacteria and cyanobacteria have two mechanisms for the uptake and transformation of selenate (ATSDR, 2003). The uptake method reduces selenate to elemental selenium, which is physically held within the algal mat. The microorganisms were found to transform soluble selenium into volatile alkyl selenium compounds. Selenious acid, a weak acid, and the diselenite ion predominate in waters between pH 3.5 and 9.

In general, selenites are less soluble in water than the corresponding selenates. In most surface waters, sodium predominates as the counter ion of selenate and selenite. Microbial activity in deep aquifers is believed to retard the selenium transport in groundwater by causing chemical reduction and precipitation (White et al., 1991; ATSDR, 2003). However, it has been shown that oxidation of exposed soils in the shallow aquifer under the Newport Bay watershed has mobilized selenium, making groundwater a primary source of selenium in the watershed.

Meixner et al. (2004) found that 90 percent of the total selenium in groundwater from the Newport Bay watershed was in the form of selenate, the most oxidized form of selenium. Of the remaining 10 percent, 8 percent was selenite and 2 percent was organic selenium. Similar relationships were observed in surface water in the upper reaches of the watershed. This was expected because the baseflow is dominated by groundwater. All storm flows measured by Meixner et al. (2004), except San Diego Creek at Campus Drive, had small concentrations of selenium that were 100 percent selenate. For the Campus Drive sampling station (average over all seasons), selenite comprised 22 percent of total selenium, with 73 and 5 percent being in the selenate and organic selenium forms, respectively. Additional data on selenium speciation will be collected in future sampling events. Those data will be used to describe transformation processes within the Newport Bay watershed.

Range of Distribution Coefficients (Kds)

The partitioning of total selenium between two compartments (e.g., sediment/particulate and dissolved phases in this case) is quantitatively described by the partitioning coefficient (Kd) (Luoma and Presser, 2000). The Kd is the ratio of selenium per unit mass in particulate material versus selenium per unit volume water, in equivalent units. Kds for soil to groundwater and sediment/particulate matter to surface water within the Newport Bay watershed were not reported in the literature reviewed. However, these values from particulate matter to water could be calculated by dividing the concentration of dissolved selenium by the concentration of particulate selenium at a sampling location if the samples were taken at the same time. Future determination of site-specific Kds will consider seasonality (i.e., variation over different flow regimes) and selenium speciation and will be calculated for several important hydrologic subunits in the watershed (e.g., San Joaquin Marsh, San Diego Creek in-line sedimentation basins, PCW, etc.).

2.2.3. Particulate and Sediment-Associated Selenium

Luoma and Presser (2000) define the particulate phases of selenium as primary producers (e.g., phytoplankton), bacteria, detritus, suspended inorganic material, and sediments. This definition also applies to the Newport Bay conceptual model. The partitioning of selenium between the dissolved and particulate phases and transformation of selenium in the particulate phases are detailed in Luoma and Presser (2000) and summarized below.

Partitioning

The partitioning reactions that determine the distribution between dissolved and particulate phases of selenium are a primary link in controlling the bioavailability and effects of selenium (Luoma and Presser, 2000). This is because particulate forms of selenium provide the primary pathway for selenium transfer to upper trophic levels within a system, and the transformation efficiency from dissolved to particulate selenium is important in determining food web concentrations of selenium. It is also important to note that selenium concentrations in the particulate phase can vary widely (as much as 100-fold) at the same dissolved concentration, and they depend on biogeochemical transformation reactions. Thus, development of site-specific Kds is important.

Transformation

Biological, redox, and physical processes are the primary reactions that transform dissolved species of selenium to particulate selenium. Luoma and Presser (2000) list five of the most important transformation reactions as follows:

- **Assimilatory biological uptake and transformation**: Microbes, plants, and microflora (phytoplankton) biochemically reduce waterborne selenium (Se^{+4}, Se^{+6}, and/or dissolved organo-selenium [Se^{-2}]) to particulate Se^{-2} via uptake. This cellular selenium is generally highly bioavailable to consumers. When the cells die, Se^{+4} and Se^{-2} are released to the water column in dissolved form or sequestered in sediments or suspended particulate matter as detrital Se^{-2}. These processes are depicted in **Figure 1**.

- **Dissimilatory (extra-cellular) biogeochemical reduction**: Bacteria transform dissolved waterborne selenium to sediment-associated phases by dissimilatory reduction. In this reaction, Se^{+4} or Se^{+6} is predominantly transformed to elemental selenium in sediments, though some organo-selenium may also be produced. The elemental selenium may then be further transformed within the sediments by reactions such as precipitation, incorporation into solid phases, or uptake by plants to ultimately form detrital organo-selenium.

- **Oxidation state**: Oxidation/reduction status is important in determining the particulate form of selenium. Because each particulate form has a different bioavailability, the form is crucial to predicting effects of selenium. Possible forms of selenium include adsorbed/coprecipitated selenite and selenate, organic selenides (either in the form of intracellular Se^{-2} or detrital Se^{-2}), or elemental selenium.

- **Adsorption**: Geochemical adsorption can occur in the water column (i.e., reduced sediments are mixed into the water column and oxidized) or at the redox interface.

- **Volatilization***:* Limited studies at Kesterson Reserve (Cooke and Bruland, 1987) and other wetland systems (Zhang and Moore, 1997; Hansen et al., 1998) indicate that up to 30 percent of incoming selenium is volatilized from a marsh/wetland system (Luoma and Presser, 2000). Although this is a potentially important release mechanism for selenium in aquatic systems (i.e., may slow selenium accumulation rates), most of the selenium has generally been found to remain in sediment. In the San Diego Creek watershed, Meixner et al. (2004) reported about 60 percent of selenium from subsurface soils (i.e., selenium contributed by groundwater seepage into San Diego Creek) makes it to the monitoring station at Campus Drive. This suggests that about 40 percent of selenium from this source is volatilized, sequestered in sediment, and/or accumulated into biota.

Range of Distribution Coefficients (Kds)

Distribution coefficients (Kds) for selenium in the Newport Bay watershed have not been published in the literature reviewed. However, these values from water to particulate matter could be calculated by dividing the concentration of particulate selenium by the concentration of dissolved selenium at a sampling location if the samples were taken at the same time. Luoma and Presser (2000) present a table of Kds for various ecosystems with reliable geochemical data. These literature-based Kds are provided in **Table 2**.

Table 2: Partitioning Between Dissolved Selenium and Particulate or Sediment Selenium (dry weight) in Ecosystems for Which Reliable Analytical Data are Available

Ecosystem	TSe_{diss} (µg/L)	TSe_{sed} (µg/g)	TSe_{sed}/ TSe_{diss} (Kd)	Reference
Kesterson Reservoir (terminal pond)	14	55	$4 X 10^3$	Presser and Piper, 1998
Belews Lake	~11	~15	$1.3 X 10^3$	Lemly, 1985a
Benton Lake Pool 1 Channel	4	10	$2.5 X 10^3$	Zhang and Moore, 1996
Benton Lake Pool 2	10.4	3.5	$0.34 X 10^3$	Zhang and Moore, 1996
Benton Lake Pool 5	0.74	0.35	$0.5 X 10^3$	Zhang and Moore, 1996
Constructed Wetland	<5-30	2.1-6.7	$0.3 X 10^3$	Hansen et al., 1998
SLD (means)	62.5	55	$0.9 X 10^3$	Luoma and Presser, 2000
Delaware: Tidal Freshwater	0.17-0.35	0.6-1.5	$4 X 10^3$	Reidel and Sanders, 1998
Diatoms			$1.1 X 10^5$	Reinfelder and Fisher, 1991
Dinoflagellate			$4.0 X 10^3$	Reinfelder and Fisher, 1991
Great Marsh, Delaware	0.01-0.06	0.3-0.7	$3 X 10^3$ - 1 $X10^4$	Velinsky and Cutter, 1991
Bay-Delta SPM 1986/1995/1996	0.1-0.4	1-8	1 - $4 X 10^4$	Cutter and Cutter, 2004
Bay-Delta sediment	0.1-0.3	0.2-0.5	1 - $5 X 10^3$	Johns et al., 1988

Notes
Source: Luoma and Presser (2000)
Kd = partitioning coefficient
SLD = San Louis Drain
SPM = suspended particulate matter
TSe_{diss} = Total selenium - dissolved
TSe_{sed} = Total selenium in sediment

2.2.4. *Bioaccumulation of Selenium*

Bioaccumulation is the combined net accumulation of a chemical from abiotic media and ingestion of chemical-containing biota.

Partitioning

Selenium bioaccumulates in both aquatic and terrestrial food webs, including higher trophic-level animals that feed on plants and lower trophic-level animals. Ingestion is the primary route of uptake in both aquatic and terrestrial food webs, and toxic effects from food-borne selenium are usually more significant than those from waterborne selenium

(Sandholm et al., 1973; Birkner, 1978; Brooks, 1984; Girling, 1984; Lemly, 1985a,b; Ohlendorf, 1989). Incidental ingestion of sediment or soil can also be a significant route of exposure to selenium, though some forms in sediment may not be readily bioavailable.

Transformation

Bioaccumulation and overall concentrations are usually higher in marine organisms than in freshwater organisms, unless there are local or regional sources that cause elevated selenium in the freshwater environment (Ohlendorf, 2003; Eisler, 2000). In freshwater biota, selenate represented about 36 percent of the total selenium (selenite and selenide made up the remainder) while in marine samples, only 24 percent of the total selenium was selenate (Cappon and Smith, 1982; Eisler, 2000). The significance of this difference is not well understood but may affect the ability of selenium to reduce toxicity of heavy metals as discussed later in this report.

Selenium is bioaccumulated in the aquatic food web. Selenite and selenate are the most common aqueous forms and are biotransformed into organic chemical species after uptake by primary producers (such as algae, phytoplankton, and rooted plants) (Ogle et al., 1988; USDI, 1998; Ohlendorf, 2003). Bioaccumulation is often a function of chemical species. Organic selenium is especially bioaccumulative, so that aquatic organisms exposed to organic selenium (such as selenomethionine) are likely to bioaccumulate much more selenium than those exposed to inorganic selenium in water (Ohlendorf, 2003). For example, Besser et al. (1989) found that selenium bioaccumulated from selenomethionine more readily than from selenite or selenate. As noted above, inorganic selenium is converted to organic selenium by organisms such as algae when it is taken up from the water. In an experimental treatment system using an algal-bacterial selenium reduction process, 80 percent of the total selenium was removed from the water, but aquatic organisms living in treated water had 2 to 4 times more selenium than those living in untreated water (Amweg et al., 2003). This illustrates the importance of understanding the cycling processes that convert selenium from one form to another, potentially increasing bioavailability and uptake (and therefore risk to consumers).

Bioaccumulation Models

Bioaccumulation of selenium from abiotic to biotic media may be modeled in several ways. The least complex of these models is a simple ratio of the concentration in the organism and the concentration in the environment. This is known as the bioaccumulation factor (BAF) for bioaccumulation from water or the biota-to-sediment accumulation factor (BSAF) for bioaccumulation from sediment. Although this technique is often employed, it is likely to be the least accurate over varying conditions (i.e., the BAF for one species in a particular waterbody may not be representative of the BAF for that same species in a different waterbody, and the BAF may vary in relation to the waterborne selenium concentration [with higher BAFs when selenium concentrations are lower]). Most importantly, this approach does not consider the effects of selenium speciation in water or particulate matter on bioaccumulation; this results in widely varying BAFs (as much as 50-fold) for a given species in different environments (Luoma and Presser, 2000). However, this approach may be useful for developing site-specific bioaccumulation values for the Newport Bay watershed using the empirical data.

Models other than the BAF or BSAF also exist. Luoma and Presser (2000) outline the methods for determining bioaccumulation using the Dynamic Multi-pathway Bioaccumulation Model (DynBaM). This model uses different experimentally established uptake rates for the different forms of dissolved and particulate selenium, as well as environmental concentrations of these forms (see Luoma and Presser, 2000, for details of the model). Two advantages of this model are:

1. Bioaccumulation can be derived for different speciation regimes.
2. Predictions of the model can be verified by comparison to analyses of selenium in tissues of resident species.

However, the model also requires some data that may not be readily available. For example, the influx rate of selenium must be calculated as part of the model (Luoma and Presser, 2000). This calculation for influx from food requires knowledge of the feeding rate for the species as well as an assimilation efficiency value that represents how well selenium is absorbed through the digestive processes of the species. Although Luoma and Presser (2000) present information needed to perform this calculation for bivalves, information for other species is not provided. Additionally, these parameters are likely to vary by site, and would, therefore, need to be determined for San Diego Creek and Newport Bay. Quantification of bioaccumulation from water and sediment/particulate matter to water column invertebrates (e.g., water boatmen) and benthic invertebrates (snails, amphipods, dragonfly larvae, mussels, shore crabs, and polychaetes) is required in the conceptual model for the Newport Bay watershed.

In another example, Byron et al. (2003) use the site-specific relationship between waterborne selenium and concentrations in invertebrates as the basis for a predictive bioaccumulation model for Kesterson Reservoir. In that example, a large dataset facilitated the development of site-specific, empirical, BAF relationships to model possible future conditions. Depending on the number and type of samples collected in the Newport Bay system, such an approach may be applicable for showing local uptake and accumulation of selenium into the food web (e.g., BAFs for water to algae, sediment to benthic invertebrates, or water to fish).

2.3. EXISTING CONCENTRATIONS OF SELENIUM

Within the San Diego Watershed/Newport Bay watershed, selenium has been measured in groundwater, surface water, sediment, and biota including benthic invertebrates, fish, watercolumn invertebrates, and bird eggs. The preliminary types and spatial distribution of available data (**Table 3**) and preliminary ranges of concentrations (**Table 4**) for the San Diego Creek watershed and Newport Bay are discussed below. The data in these tables is only preliminary, and is meant to give an idea of the types of data and ranges of concentrations. A current analysis of the available data will be included in separate reports (i.e., those for sources and loads and identification of data gaps). Eisler (2000) presents a comparison of selenium concentrations in abiotic media and biota that have been measured across various ecosytems. This compilation may provide a framework for understanding the magnitude of selenium contamination in the watershed compared to other sites. However, it should be noted that site-specific characteristics affecting the distribution and availability of selenium within a system make direct comparisons among different sites uncertain. Potential impacts of selenium in the Newport Bay watershed will be evaluated in a site-specific manner, and are not considered relative to other sites such as Kesterson.

Table 3: Preliminary Data Availability for Selenium Measurements in the Newport Bay Watershed

	Abiotic Samples			Biotic Samples			
	Surface Water	**Ground Water**	**Sediment**	**Benthic Inverts**	**Fish**	**Water-Column Invertebrates**	**Bird Eggs**
San Diego Creek & Tributaries							
Peters Canyon Wash	●	○	○	●	●	○	○
El Modena Channel	●	○	○	○	○	○	○
Coast Mesa Channel	●	○	○	○	○	○	○
Santa Fe Channel	●	○	○	●	●	●	○
Como Channel (along Culver outlet)	●	○	○	○	○	○	○
San Diego Creek	● [a,b]	●	●	○	●	●	●
Barranca Channel	●	○	○	○	○	○	○
Lane Channel	●	○	●	○	○	○	○
Big Canyon Wash	●	○	●	○	○	○	○
San Joaquin Channel	○	○	○	○	○	○	○
Sand Canyon Wash	○	○	○	○	○	○	○
Bonita Canyon Channel or Creek	●	○	●	○	○	○	○
Santa Ana-Delhi Channel	●	○	○	○	○	○	○
Santa Isabella Channel	●	○	○	○	○	○	○
Upper Newport Bay	○	○	●	●	●	○	●
Lower Newport Bay	○	○	●	○	●	○	○
Nurseries [c]							
Hicks Canyon Wash (also SDC Tributary)	●	○	○	○	○	○	○
Central Irvine Channel (also SDC Tributary)	●	○	○	○	○	○	○
Hines Nursery Channel	●	○	○	○	○	○	○
Marshburn Channel	○	○	○	○	○	○	○
San Joaquin Marsh							
Inlet	○†	--	●	●	●	●	--

Table 3: Preliminary Data Availability for Selenium Measurements in the Newport Bay Watershed

	Abiotic Samples			Biotic Samples			
	Surface Water	**Ground Water**	**Sediment**	**Benthic Inverts**	**Fish**	**Water-Column Invertebrates**	**Bird Eggs**
Pond	○†	--	●	○	●	●	●
Outlet	○†	--	○†	○	○†	○†	--
Historic Marsh Area	--	●	--	--	--	--	--
Groundwater Cleanup	○	●	--	--	--	--	--
Ground Water Treatment Facility	○	●	○	○	○	○	○
Tustin Marine Corps Air Station (MCAS)	○	●	○	○	○	○	○
El Toro MCAS	○	●	○	○	○	○	○
Groundwater Dewatering							
Jamboree Undercrossing	--	●	--	--	--	--	--
Culver Undercrossing	--	●	--	--	--	--	--
Urban Runoff (Storm Drain) [d]							
Circular Drain	○	●	○	○	○	○	○
Valencia Drain	○	●	○	○	○	○	○
Warner Drain	○	●	○	○	○	○	○
Polaris Drive (into UNB)	●	○	--	--	--	--	--
Archev V-Ditch (into LNB)	●	○	--	--	--	--	--
Agricultural Runoff	○	○	--	--	--	--	--
Open Space and Hillside Runoff	●	○	●	--	--	--	--
Groundwater springs and seeps [e]	--	●	--	--	--	--	--
Groundwater Wells [e]	--	●	--	--	--	--	--

Notes

[a] San Diego Creek at Campus Drive

[b] San Diego Creek at Harvard Ave.

[c] These channels may receive water from other sources; however, discharge from nurseries is the primary source. Therefore, selenium in these channels is considered representative selenium runoff from nurseries.

[d] These are two storm drains containing discharges from urban runoff. Other data representative of urban runoff are likely available, and will be added at a later time.

[e] Groundwater data consist of various channels, washes, springs, weepholes, wells, sumps, and drains.

In some cases, a location within the watershed was identified; however, the data were not readily available for the development of this preliminary table. Therefore, the sampling location is listed, but the types of data collected at that location have not been identified.

○ = Data are not available

Table 3: Preliminary Data Availability for Selenium Measurements in the Newport Bay Watershed

	Abiotic Samples				Biotic Samples			
	Surface Water	Ground Water	Sediment		Benthic Inverts	Fish	Water-Column Invertebrates	Bird Eggs

● = Data are available

○† = Need to obtain actual data values from California State University - Los Angeles

-- = Not Applicable

UNB = Upper Newport Bay; LNB = Lower Newport Bay

Table 4: Preliminary Concentration Ranges for Selenium in Abiotic and Biotic Media of the Newport Bay Watershed

Location	Abiotic Samples			Biotic Samples			
	Surface Water (µg/L)	Ground Water (µg/L)	Sediment (mg/kg)	Benthic Inverts (mg/kg)	Fish (mg/kg)	Water-Column Invertebrates (mg/kg)	Bird Eggs (mg/kg)
Tributaries of San Diego Creek							
Peters Canyon Wash							
Moore, 2005	2 - 36	○	○	○	○	○	○
Meixner et al., 2004	1.93 - 31.60	○	○	○	○	○	○
Hibbs and Lee, 2000	15 - 162	○	○	○	○	○	○
Horne Associates, 2003	30	○	○	10.7	29.9	○	○
Horne, 2004	30	○	○	○	○	○	○
El Modena Channel							
Meixner et al., 2004	1.96 - 4.32	○	○	○	○	○	○
Hibbs and Lee, 2000	<4 - 11	○	○	○	○	○	○
Coast Mesa Channel							
Moore, 2005	2 - 18	○	○	○	○	○	○
Denitrification Plant Outlet							
Meixner et al., 2004	○	38.33	○	○	○	○	○
The Department, 2005	○	2.8 - 4.5	○	○	○	○	○
Hibbs and Lee, 2000	○	○	○	○	○	○	○
Santa Fe Channel							
Horne, 2004	17	○	○	○	12.5 [a]	3.7 [b]	○
Meixner et al., 2004	15.3-15.8	○	○	○	○	○	○
Hibbs and Lee, 2000	<4 - 32	○	○	○	○	○	○
Horne Associates, 2003	16	○	○	2.6 - 4.9	12.5	2.7	○

Table 4: Preliminary Concentration Ranges for Selenium in Abiotic and Biotic Media of the Newport Bay Watershed

Location	Abiotic Samples Surface Water (µg/L)	Ground Water (µg/L)	Sediment (mg/kg)	Biotic Samples Benthic Inverts (mg/kg)	Fish (mg/kg)	Water-Column Invertebrates (mg/kg)	Bird Eggs (mg/kg)
Como Channel (along Culver outlet)							
Meixner et al., 2004	12.01 - 27.8	○	○	○	○	○	○
Hibbs and Lee, 2000	<4 - 38	○	○	○	○	○	○
Moore, 2005	<2 - 35	○	0.02 - 3	○	○	○	○
Meixner et al., 2004	3 – 38.6	3.2 - 102	○	○	○	○	○
Hibbs and Lee, 2000	4 - 19	○	○	○	○	○	○
Horne, 2004	<2 - 31	○	○	○	○	○	○
Byron, 2005	○	○	0.68 - 3.12	○	17	13.6	○
Santolo, 2005	○	○	○	○	○	○	7.0 - 14.5
San Diego Creek – Reach 2							
Meixner et al., 2004	1.1	2.9 – 12.8	○	○	○	○	○
Barranca Channel							
Meixner et al., 2004	1.85 - 12.30	○	○	○	○	○	○
Hibbs and Lee, 2000	12 - 13	○	○	○	○	○	○
Lane Channel							
Moore, 2005	0.4 - 75	○	0.11 - 0.7	○	○	○	○
Meixner et al., 2004	13.9 - 14.5	○	○	○	○	○	○
Hibbs and Lee, 2000	18 - 25	○	○	○	○	○	○
Big Canyon Wash							
Moore, 2005	2 - 60	○	0.02 - 14	○	○	○	○
San Joaquin Channel							
Sand Canyon Wash							

Table 4: Preliminary Concentration Ranges for Selenium in Abiotic and Biotic Media of the Newport Bay Watershed

Location	Abiotic Samples Surface Water (µg/L)	Ground Water (µg/L)	Sediment (mg/kg)	Biotic Samples Benthic Inverts (mg/kg)	Fish (mg/kg)	Water-Column Invertebrates (mg/kg)	Bird Eggs (mg/kg)
Bonnita Canyon Channel or Creek							
Hibbs and Lee, 2000	14	○	○	○	○	○	○
Moore, 2005	0.4 - 32	○	0.5 - 0.61	○	○	○	○
Santa Ana-Delhi Channel							
Meixner et al., 2004	8.43	○	○	○	○	○	○
Moore, 2005	1 - 30	○	○	○	○	○	○
Hibbs and Lee, 2000	18	○	○	○	○	○	○
Santa Isabella Channel							
Moore, 2005	2 - 6.1	○	○	○	○	○	○
Upper Newport Bay							
Allen et al., 2004	○	○	○	○	0.28 - 1.92	○	○
Bay et al., 2004	○	○	1.75	○	○	○	○
Byron, 2005	○	○	2.04 - 3.6	2.31	5.24	○	○
Santolo, 2005	○	○	○	○	○	○	2.9 – 10.7
Lower Newport Bay							
Allen et al., 2004	○	○	○	○	0.22 - 0.46	○	○
Bay et al., 2004	○	○	1.28	○	○	○	○
Nurseries [a]							
Hicks Canyon Wash							
Hibbs and Lee, 2000	6	○	○	○	○	○	○
Central Irvine Channel							
Moore, 2005	2 - 20	○	○	○	○	○	○
Meixner et al., 2004	5.54 - 6.32	○	○	○	○	○	○
Hibbs and Lee, 2000	11	○	○	○	○	○	○

Table 4: Preliminary Concentration Ranges for Selenium in Abiotic and Biotic Media of the Newport Bay Watershed

Location	Abiotic Samples Surface Water (µg/L)	Ground Water (µg/L)	Sediment (mg/kg)	Biotic Samples Benthic Inverts (mg/kg)	Fish (mg/kg)	Water-Column Invertebrates (mg/kg)	Bird Eggs (mg/kg)
Hines Nursery Channel							
Moore, 2005	20	○	○	○	○	○	○
Marshburn Channel							
San Joaquin Marsh (IRWD)							
Inlet							
Meixner et al., 2004	21.14	○	○	○	○	○	○
Byron, 2005	○	○	1.36 - 2.60	3.25	5.62	4.17	○
Pond	○	○	○				
Horne, 2004	○	○	○	○	○	○	2.6 - 17.2
Byron, 2005	○	○	3.1 – 4.26	○	2.88	1.76	○
Santolo, 2005	○	○	○	○	○	○	3.5
Outlet	○	○	○	○	○	○	--
Historic Marsh Area							
Hibbs and Lee, 2000	--	20 - 478	--	○	○	○	○
Groundwater Cleanup				--	--	--	--
Groundwater Dewatering	--			--	--	--	--
Jamboree Undercrossing	--			--	--	--	--
Loving, 2005a	○	○	○	--	--	--	--
Loving, 2005b	--	<6 - 49	--	--	--	--	--
Culver Undercrossing							
Loving, 2005a	--	0.07 - 10	--	--	--	--	--
Loving, 2005b	--	<0.06 - 34	--	--	--	--	--
Urban Runoff (Storm Drain) [b]				--	--	--	--
Polaris Drive (into UNB)				--	--	--	--
Swafford, 2005	5.42 - 9.57	○	--	--	--	--	--

Table 4: Preliminary Concentration Ranges for Selenium in Abiotic and Biotic Media of the Newport Bay Watershed

	Abiotic Samples			Biotic Samples			
Location	**Surface Water (µg/L)**	**Ground Water (µg/L)**	**Sediment (mg/kg)**	**Benthic Inverts (mg/kg)**	**Fish (mg/kg)**	**Water-Column Invertebrates (mg/kg)**	**Bird Eggs (mg/kg)**
Archev V-Ditch (into LNB)				--	--	--	--
Swafford, 2005	5.25 - 8.81	○	--	--	--	--	--
Agricultural Runoff				--	--	--	--
Open Space and Hillside Runoff				--	--	--	--
Detention Basins							
Round Canyon							
Meixner et al., 2004	○	○	0.623-2.011	○	○	○	○
Portola							
Meixner et al., 2004	○	○	0.116-0.144	○	○	○	○
Hicks Canyon							
Meixner et al., 2004	1 - 11	○	0.218-0.329	○	○	○	○
Groundwater							
Channels and Washes	--		--	--	--	--	--
Meixner et al., 2004	--	4.47-114.04	--	--	--	--	--
Springs	--		--	--	--	--	--
Meixner et al., 2004	--	4.71 - 177.45	--	--	--	--	--
Hibbs and Lee, 2000	--	14 - 178	--	--	--	--	--
Weepholes	--		--	--	--	--	--
Meixner et al., 2004	--	13.81 - 81.08	--	--	--	--	--
Hibbs and Lee, 2000	--	7 - 178	--	--	--	--	--
Wells	--		--	--	--	--	--
CDM, 2001	--	5.6 - 15.6	--	--	--	--	--
Meixner et al., 2004	--	2.17 - 47.23	--	--	--	--	--
Hibbs and Lee, 2000	--	18 - 200	--	--	--	--	--

Table 4: Preliminary Concentration Ranges for Selenium in Abiotic and Biotic Media of the Newport Bay Watershed

Location	Abiotic Samples				Biotic Samples			
	Surface Water (µg/L)	Ground Water (µg/L)	Sediment (mg/kg)		Benthic Inverts (mg/kg)	Fish (mg/kg)	Water-Column Invertebrates (mg/kg)	Bird Eggs (mg/kg)
Sumps	--		--		--	--	--	--
Meixner et al., 2004	--	20.27	--		--	--	--	--
Groundwater Drains	--		--		--	--	--	--
Meixner et al., 2004	--	82.49 - 183.25	--		--	--	--	--

Notes

[1] Primarily mosquitofish but dragonfly larvae were also included.

[2] Comprised mostly of chironomid larvae

[a] These channels may receive water from other sources; however, discharge from nurseries is the primary source. Therefore, selenium in these channels is considered representative selenium runoff from nurseries.

[b] These are two storm drains containing discharges from urban runoff. Other data representative of urban runoff are likely available, and will be added at a later time.

Significant figures presented are those presented in data sources. In subsequent data presentations, appropriate significant figures will be used.

○ = Data are not available

-- = Not Applicable

LNB = Lower Newport Bay

IRWD = Irvine Ranch Water District

µg/g = micrograms per liter

mg/kg = milligrams per kilogram (dry weight)

UNB = Upper Newport Bay

Table 3 is intended as a quick reference to indicate which types of data are available for both point and non-point sources (e.g., tributaries, nurseries groundwater dewatering, and groundwater seepage), as described in the TMDL report (USEPA, 2002). **Table 4** depicts the selenium concentration ranges for each source based on available data for abiotic (surface water, groundwater, sediment) and biotic matrices (fish, benthic invertebrates, and bird eggs). Following each source, the available literature and the selenium concentration ranges for that study are listed. It should be noted that the legacy data for the watershed are currently being collected and evaluated. These data are not included in **Tables 3** and **4**. Therefore, additional data made available at a later time may fill in gaps that were identified as data gaps and change the maximum and minimum concentration range presented.

Within the San Diego Creek watershed, surface water is the most widely represented of the available data. Sediment data are more limited in spatial distribution, although many areas of the watershed are represented. Selenium has also been measured in a diversity of biota utilizing the watershed (algae, fish, benthic invertebrates, water-column invertebrates, and bird eggs), but to a more limited spatial extent than measurements in surface water and sediment (**Table 3**). Among all channels and tributaries within the San Diego Creek watershed, Peters Canyon Wash was documented with the highest surface water concentration (162 µg/L at Irvine Center Drive, sampled in 1999 [Hibbs and Lee, 2000]) (**Table 4**). Groundwater sources were major contributors of selenium, with maximum concentrations up to 478 µg/L in groundwater from the historical swamp area (Swamp of the Frogs). The highest measured concentration of selenium in the preliminary sediment data was measured in Big Canyon Wash (14 mg/kg dry weight [dw]; **Table 4**). Concentrations of selenium in fish (30 mg/kg dw) and benthic invertebrates (11 mg/kg dw]) were greatest in Peters Canyon Wash (**Table 4**), which is not surprising given that Peters Canyon Wash had the highest surface water concentrations among the tributaries (note: no sediment data have been identified at this time for comparison). In bird eggs, concentrations up to 17 mg/kg dw were measured in the San Joaquin Marsh.

Selenium data for sediment are available for both Upper and Lower Newport Bay (**Table 3**). Additionally, selenium has been measured in fish collected from Upper and Lower Newport Bay (**Table 3**). Both sediment and fish concentrations were greater in Upper Newport Bay (1.3 and up to 9.6 mg/kg dw, respectively) than in Lower Newport Bay (1.28 and up to 2.3 mg/kg dw, respectively; Bay et al., 2004 and Allen et al., 2004) (**Table 4**).

Temporal trends in the analytical data will be evaluated where sufficient data are available.

2.4. EFFECTS OF SELENIUM ON FISH AND WILDLIFE

Selenium is an essential trace element for animals, and is a component of glutathione peroxidase (GSH-PX), which aids in the protection of tissues against peroxidation by destroying hydrogen peroxide or organic hydroperoxides (Ohlendorf, 2003). The presence of selenium at increased dietary levels results in the replacement of sulfur in some metabolic pathways disrupting certain biological processes. Selenite and selenate are readily absorbed through the small intestine in animals. Selenides and elemental selenium are poorly absorbed. Selenomethionine has been found to be the best surrogate form of selenium in experimental studies with fish and birds to represent environmental exposures. Elemental selenium (and other insoluble forms) appears to be least toxic. About 70 to 80 percent of the inorganic selenium intake is quickly excreted in the urine, breath, perspiration, and bile. The remaining selenium is eliminated after becoming bound or incorporated into blood and tissue proteins (Ohlendorf, 1989).

Studies describing the effects of selenium on fish and wildlife have been summarized in several publications such as Lemly and Smith (1987), Luoma and Presser (2000), and Eisler (2000). In addition, site-specific toxicity studies have been conducted for San Diego Creek (Lee and Taylor, 2001; Bay et al., 2003) and Newport Bay (Bay et al., 2004). The effects concentrations presented in Luoma and Presser (2000) are summarized below and in **Tables 5** through **8**. These data represent an initial compilation of effects values for selenium. However, some of these data may not be relevant to the Newport Bay watershed, and additional data may be available. Therefore, effects data ultimately used for the Newport Bay watershed may differ from those presented here.

Additional thresholds may be utilized for the Newport Bay watershed, as needed.

Table 5: Examples of Thresholds for Selenium Effects (Health, Reproductive, Teratogenesis, or Survival) in Fish Based on Concentrations of Selenium in Food

Concentration in Food (μg Se/g, dry weight)	Approach	Response Observed	References
3-7 >7		Marginal effects Substantive effects	Presser et al. 2004
0.1-0.5	Lab	Nutritionally sufficient range. Additional nutritional benefits often observed up to 1 μg/g. Diets containing < 0.1 μg/g often associated with deficiency syndrome.	Hodson and Hilton, 1983 as cited in Lemly, 1998a
3-8	Lab, field, and synthesis	Reproductive impairment (similar thresholds for birds, Skorupa and Ohlendorf, 1992; Skorupa, 1998b).	e.g., Engberg et al., 1998; Skorupa, 1998a,b; Lemly, 1998a;b, Hamilton et al., 1996; 2000b
2-5	Belews Lake, North Carolina (1996)	Teratogenesis in fry of four recovering fish species.	Lemly, 1993; 1997b
5	Lab	Winter stress syndrome (includes mortality) in juvenile bluegill.	Lemly, 1993
9-13	Lab, field, and synthesis	Reduced growth and/or mortality in rainbow trout and bluegill.	Goettl and Davies, 1978; Hilton et al., 1980; and Cleveland et al., 1993 as cited in Hamilton et al., 2000a; Skorupa, 1998b
5-10 (in prey [fish])	Lab Freshwater	Growth and survival affected in chinook salmon (swim-up) larvae (SLD diet).	Hamilton et al., 1990
18 (in prey [fish])	Lab Brackish Water	Growth reduced in chinook salmon fingerlings (SLD diet).	Hamilton et al., 1990

Table 5: Examples of Thresholds for Selenium Effects (Health, Reproductive, Teratogenesis, or Survival) in Fish Based on Concentrations of Selenium in Food

Concentration in Food (µg Se/g, dry weight)	Approach	Response Observed	References
30-35	Synthesis	Complete reproductive failure in adult sensitive species (e.g., bluegill).	Coyle et al., 1993 and Woock et al., 1987 as cited in Skorupa, 1998b
20-80	Belews Lake, North Carolina (1973-1984)	Massive poisoning of fish community: 16 of 20 species disappear; two species rendered sterile, but persisted as aging adults; one occasionally re-colonized as adults; and one unaffected. Deformities in survivors. Some recovery after Se removal.	Cumbie and Van Horn, 1978; Lemly, 1985a; 1997b; 1998a
>100	Kesterson Reservoir, California	Massive poisoning of fish and birds, including deformities in coots, grebes, ducks, and stilts.	Saiki and Lowe, 1987; Ohlendorf, 1989; Presser and Ohlendorf, 1987

Notes:

Source: Modified from Luoma and Presser (2000)

Se = selenium

SLD = San Luis Drain

Table 6: Examples of Selenium Toxicity Effects on Birds Based on Concentrations of Selenium in Diet

Concentration in Food (µg Se/g, dry weight)	Response Observed	References
4	Lower-bound dietary level for reproductive effects (duckling deformities).	Heinz, 1996
4.87	Level at which mallards had 10% reduced egg hatchability.	Ohlendorf, 2003
5	Level at which would 15 µg Se/g dry-weight would accumulate in bird eggs.	Skorupa and Ohlendorf, 1991
6 - 9	Reduced egg hatchability; 6 µg/g in food is the lower-bound dietary threshold above which egg hatchability is reduced (if Se assimilation in the wild is close to that observed in the laboratory).	Ohlendorf, 1989
8	Compared to 1 µg/g , 8 µg /g causes: 33% reduction in hatching success in mallard; 17% reduction in survival of ducklings; 7% deformities on the unhatched eggs.	Heinz et al., 1989 Stanley et al., 1996
>8	Upper dietary threshold above which deformities rose rapidly; 43% reduction in 6-day old ducklings.	Heinz, 1996
16	Complete reproduction failure in mallards.	Heinz et al., 1989
20	Food avoidance; weight loss; mortality (enhanced during cold winter)	Heinz and Fitzgerald, 1993

Notes

Toxicity effects presented in this table were adapted from Luoma and Presser (2000)

Based on the toxicity effects of Se diet, Luoma and Presser (2000) concluded that the dietary threshold for birds is between 5 and 9 µg /g.

Table 7: Examples of Thresholds for Selenium Effects (Health, Reproductive, Teratogenesis, or Survival) in Fish Based on Selenium Concentrations in Tissue of Fish

Effect/Threshold	Location	Concentration in Tissue (mg Se/g, dry weight)	Reference
Deformities/tissue	Field	• 10-20 (in whole homogenate) • 6 – 12 (in muscle [fillets]) • 20-40 (in viscera)	Lemly, 1998a
Percent deformed larvae, fry, juveniles, or adults (e.g., centrarchids)/whole-body	Field	• 5-10 (whole-body = onset of deformities (<6%) in larvae, fry, juveniles, and adults) • 11-20 (whole-body = <11% deformities in juveniles and adults) • 25-35 (whole-body = rapid rise in rate of deformities in larvae of some species [35-65%]) • 40-50 (rapid rise in rate of deformities = 20 – 30% in juveniles and adults) • 30 – 40 (whole body = 80% deformities in larval fish) • 70 - 90 (whole body = 70% deformities in juveniles and adults)	Lemly, 1997a
Growth and survival of salmon (larval; fingerling)/whole-body	Lab (SLD diet) and synthesis	• 4-6 (whole-body)	Hamilton et al., 1990; 2000a
Survival of razorback sucker larval fish/whole-body	Field	• 4-14 (whole-body)	Hamilton et al., 1996
Thresholds whole body (sensitive species)	Synthesis	• 4-6	Skorupa, 1998b

Table 7: Examples of Thresholds for Selenium Effects (Health, Reproductive, Teratogenesis, or Survival) in Fish Based on Selenium Concentrations in Tissue of Fish

Effect/Threshold	Location	Concentration in Tissue (mg Se/g, dry weight)	Reference
Thresholds -whole-body -skeletal muscle -liver -ovary and egg -larvae and fry	Synthesis	• 5-7 • 6-8 • 15-20 • 5-10 (6-17, terata) • 8-12 (5-12, terata)	Lemly, 1998b
Thresholds -whole-body -ovary	Synthesis	• 6 (coldwater) - 9 (warmwater) • 17	Deforest et al., 1999
Thresholds whole-body	Synthesis	• 4-12	Engberg et al., 1998
Thresholds whole-body	Synthesis	• 4-6 Marginal effects • >6 Substantive effects	Presser et al. 2004

Notes:

Source: Modified from Luoma and Presser (2000)

SLD = San Luis Drain

Table 8: Examples of Thresholds for Selenium Effects (Health, Reproductive, Teratogeneiss, or Survival) in Birds Based on Selenium Concentrations in Bird Eggs.

Selenium in Tissue (µg Se/g, dry weight)	Thresholds			References
	Embryo Deformity	Hatchability	Other	
Egg	13-24 (mean egg; field, western and northern plains of U.S.)	--	--	Skorupa and Ohlendorf, 1991
Egg	12-15 (lab, mallard and chicken)	--	--	Heinz, 1996
Egg	--	12.5 (EC10)	--	Ohlendorf, 2003
Egg	--	10 (Kesterson Reservoir, CA)	--	Skorupa and Ohlendorf, 1991; Skorupa, 1998a;b
Egg	--	6 (mean; Salton Sea, CA)	--	Skorupa 1998a;b
Egg	--	4-10 (Tulare Basin, CA)	--	Skorupa 1998a;b
Egg (taxa specific)	15-20 (duck) 18-25 (stilt) 38-60 (avocet)	--	--	Skorupa, 1998a;c; pers. comm., 2000
Egg (impared reproduction*)	--	>6 to >9*	--	Engberg et al., 1998; Skorupa, 1998a;b; Lemly, 1998b
Egg	--	--	6-10 marginal effect >10 substantive effect	Presser et al., 2004

Notes:

Source: Modified from Luoma and Presser (2000)

* Presented as reproductive impairment and juvenile and adult toxicity.

EC10 = 10 percent effects concentration

2.4.1. Relating Selenium Concentrations in Diet to Effects in Receptors

Fish

Eggs and larvae of fish and amphibians may be the most sensitive stages of vertebrate animals to direct exposure to waterborne selenium. Excess selenium in the diet of fish leads to substitution of selenium for sulfur during protein synthesis (Lemly, 1998a). This substitution disrupts normal chemical bonds resulting in improperly formed or dysfunctional proteins and enzymes affecting sub-cellular, cellular, organ, and system functions. Effects include teratogenicity in developing embryos, reduced survival of fry, and reduced health and survival of adult fish (Sorensen, 1986). Typical deformities include scoliosis, missing or deformed fins, missing or deformed gills and gill covers, abnormally shaped head, missing or deformed eyes, and deformed mouth (Lemly, 1998a). Parental transfer of selenium to eggs and larvae of fish can be lethal or teratogenic (Ohlendorf, 2003).

In general, fish studies indicate that when selenium concentrations are elevated, sensitive fish species disappear due to direct mortality or reproductive failure while a few tolerant species persist (Garrett and Inman, 1984; Sorensen, 1988; Vencil, 1986; NRC, 1989; Hamilton, 2004). Dietary exposure of fish to concentrations of selenium greater than 3 µg/g dw results in accumulation in developing eggs, with dietary concentrations of 5 to 20 µg/g dw exceeding the threshold for teratogenic effects in the embryo (**Table 5**). In two case studies (Belews Lake and Kesterson Reservoir), most fish species were absent when their invertebrate prey reached concentrations of 20 to 80 µg/g dw (Belews Lake) or 100 µg/g dw (Kesterson).

In a recent study, Bay et al. (2003) exposed rainbow trout (*Oncorhynchus mykiss*) to a diet spiked with selenomethionine at three concentrations (9.2, 16.6, or 22.6 µg/g dw) for 90 days. Body weight and fork length were reduced at all exposure concentrations compared to the controls. Therefore, a lowest observed effect concentration (LOEC) of 9.2 µg/g dw was identified. However, some concerns regarding this study have been raised, and these data will only be used if determined to be applicable to the watershed.

Birds

Multiple studies have investigated the effects of dietary exposure of selenium to birds (**Table 6**). Avian embryos are highly sensitive to the toxic effects of selenium (Poley and Moxon, 1938; Thapar et al., 1969; Arnold et al., 1973; NAS-NRC, 1976; El-Begearmi et al., 1977; Ort and Latshaw, 1978; Ohlendorf, 1989, 2003). Hatchability of fertile eggs is considered the most sensitive endpoint. Dabbling ducks, such as mallards and cinnamon teal, are among the most sensitive species (USDI, 1998). Adverse effects such as reduced hatching success and reduced survival of ducklings were observed at a concentration of 8 µg /g dw selenomethionine fed to mallards (Heinz et al., 1989; Stanley et al., 1996). For teratogenic effects, a threshold of 4 to 8 µg /g dw has been identified (Heinz, 1996).

Several researchers have observed that selenium concentrations in bird eggs are similar to or greater than (1 to 4 times) the dietary concentration (Ohlendorf, 1989; Heinz et al., 1989). Based on this information, dietary concentrations greater than 3 µg selenium/g dw could yield egg concentrations associated with embryo teratogenesis. Additionally, dietary levels from 6 to 9 µg/g dw are known to reduce the hatchability of chicken eggs (Ohlendorf, 1989), but reproductive impairment can result from diets of only 3-8 µg/g dw (Wilber, 1980; Martin, 1988; Heinz, 1996; USDI, 1998). Ohlendorf (2003) used the results of six studies with mallards to determine the selenium concentration in diet that was associated with reduced egg hatchability. A dietary concentration of 4.87 µg/g dw was associated with a 10 percent reduction in hatchability.

2.4.2. Relating Selenium Concentrations in Receptor Tissues to Effects

Fish

Tissue concentrations that have been associated with adverse effects in fish are listed in **Table 7**. From these data, effects may occur at whole-body selenium concentrations as low as 4 to 6 µg/g dw, with consistent evidence of teratogenesis and reproductive failure at whole body concentrations greater than 15 µg/g dw (**Table 7**). It has also been shown that the occurrence of deformities increases rapidly when selenium concentrations in fish eggs are greater than 10 µg/g dw. In addition to identifying a dietary LOEC, Bay et al. (2003) measured selenium accumulation in rainbow trout exposed to three dose levels for 90 days. The whole-body concentration associated with reduced growth was 0.51 µg/g dw. However, it should be noted that this effect level is less than background values for fish tissue (< 4 µg/g dw) reported in USDI (1998).

Birds

Because the embryo is the avian life stage that is most sensitive to selenium, monitoring of eggs is a good protocol to determine impacts on avian species utilizing the Newport Bay watershed. **Table 8** presents egg tissue thresholds for adverse effects to avian species. Based on these studies, embryo deformities may occur at selenium concentrations in eggs exceeding 12 µg/g dw, with the avocet being the least sensitive of several species tested (**Table 8**). Egg hatchability was found to be a more sensitive endpoint with thresholds ranging from 4 to 10 µg/g dw (hatchability decreased rapidly at egg concentrations greater than 10 µg/g dw). Using the results of six studies with mallards, Ohlendorf (2003) determined that egg concentrations of 12.5 µg selenium/g dw resulted in a 10 percent reduction in hatchability.

2.4.3. Site-specific Toxicity Studies

Several toxicity studies have been conducted using water and sediment collected from San Diego Creek and Newport Bay. Some basic information on these studies (e.g., species tested, toxicity endpoints, toxicity identification evaluation, media analyzed, location and source) is presented in **Table 9**. These studies are briefly described below.

Table 9: Accumulation and Toxicity Effect Data Available for the San Diego Creek Watershed and Upper Newport Bay

Species	Toxicity Endpoint			Bioaccumulation	TIE	Media	Lab/Field	Location	Source
	Survival	Reproduction	Growth						
Daphnids (*Ceriodaphnia dubia*)	●	○	○	●	●	Water	Lab	San Diego Creek Watershed [a]	Lee and Taylor, 2001
Mysid (*Americamysis bahia*)	●	○	○	●	●	Water	Lab	San Diego Creek Watershed [a]	Lee and Taylor, 2001
Fathead Minnow Larvae (*Pimephales promelas*)	●	○	○	●	○	Water	Lab	San Diego Creek Watershed [a]	Lee and Taylor, 2001
Phytoplankton (*Selenastrum capricornutum*)	○	○	●	●	○	Water	Lab	San Diego Creek Watershed [a]	Lee and Taylor, 2001
Daphnids (*Ceriodaphnia dubia*)	●	●	○	○	●	Water	Field	San Diego Creek - Campus Drive Bridge	Bay et al., 2003
Phytoplankton (*Selenastrum capricornutum*)	○	○	●	○	●	Water	Field	San Diego Creek - Campus Drive Bridge	Bay et al., 2003
Fish (*Oncorhynchus mykiss*)	○	○	●	●	○	Water	Lab	Used a spiked water	Bay et al., 2003
Amphipod (*Eohaustorius estuarius*)	●	○	○	○	●	Sed/PW	Field	Upper Newport Bay/Rhine Channel (LNB)	Bay et al., 2004
Sea Urchin (*Strongylocentrotus purpuratus*)	○	●	○	○	●	Water/PW	Field	Upper Newport Bay/Rhine Channel (LNB)	Bay et al., 2004

Notes

[a] Multiple locations within the watershed (San Diego Creek at Campus Drive and Harvard Avenue, Peters Canyon Channel at Barranca Parkway and at Walnut Avenue, Hines Channel at Irvine Boulevard, San Joaquin Channel at University Drive, Santa Ana Delhi Channel at Mesa Drive, Sand Canyon Avenue at the northeast corner of Irvine Boulevard, East Costa Mesa Channel at Highland Drive, and Central Irvine Channel at Monroe).

PW = Pore Water

TIE = Toxicity Identification Evaluation

○ = Data are not available

● = Data are available

-- = Not Applicable

San Diego Creek Watershed

Since the early 1990s, toxicity studies of urban and agricultural stormwater runoff/drainage in the Newport Bay watershed have been conducted. These studies indicated that the waterbodies within the watershed are impaired (Lee and Taylor, 2001). From 1997 through 2000, Lee and Taylor (2001) conducted over 500 toxicity tests of stormwater runoff and baseline flow in the watershed. Sampling locations included San Diego Creek at Campus Drive and Harvard Avenue, Peters Canyon Channel at Barranca Parkway and at Walnut Avenue, Hines Channel at Irvine Boulevard, San Joaquin Channel at University Drive, Santa Ana Delhi Channel at Mesa Drive, Sand Canyon Avenue at the northeast corner of Irvine Boulevard, East Costa Mesa Channel at Highland Drive, and Central Irvine Channel at Monroe. Although toxicity to *Ceriodaphnia dubia* and *Americamysis bahia* (formerly *Mysidopsis bahia*) was observed, the organophosphate pesticides, diazinon and chlorpyrifos, and "unknown constituents" were identified as the most likely cause. Selenium was not excluded as a possible contributor to toxicity because toxicity identification studies for metals were not conducted. Toxicity to fathead minnow larvae and algae was not observed.

Subsequent to the studies by Lee and Taylor (2001), Bay et al. (2003) conducted a two-part study consisting of 1) analysis of dry and wet weather surface water samples from San Diego Creek for toxicity assessment, toxicity identification, and metals concentrations; and 2) a laboratory study of the effects of selenium bioaccumulation on larval rainbow trout (results of this second part are described in Sections 2.4.1 and 2.4.2 above). For the first part of the study, surface water samples were collected at the Campus Drive Bridge during wet weather and dry weather. Two discrete samples were collected each day, with the wet weather objective of getting one sample for the initial flush and one during peak flow. Toxicity tests included the chronic survival and reproduction bioassay for a water flea (*Ceriodaphnia dubia*), and a chronic cell growth test for a fresh water alga (*Selenastrum capricornutum*). Results indicated that toxicity was present in 6 of the 10 samples (includes both wet and dry weather) collected over five days between March 2002 and February 2003. Selenium concentrations were greatest in the low-flow samples, and nearly all (in some cases 100 percent) was in the dissolved phase. Additionally, all samples, except for the second March wet-weather sample exceeded the proposed TMDL target value of 5 μg/L. Despite these exceedances of the TMDL target value, the measured selenium concentrations (up to 25 μg/L**)** were well below the median effect concentration for *Ceriodaphnia* reproduction of 870 μg/L. The authors used the following four lines of evidence to conclude that trace metals such as selenium were unlikely to cause the observed toxicity:

1. The variation in selenium concentrations among samples did not correspond to variations in toxicity.

2. There was no consistent pattern of toxicity between the two test species (i.e., sometimes effects were seen in *Ceriodaphnia*, but not *Selenastrum* and vise versa).

3. The magnitude of toxicity declined over time. This suggests that the toxicant responsible for the observed toxicity was an organic rather than a metal.

4. The toxicity identification evaluations (TIEs) for several wet-weather samples resulted in a reduction in reproductive toxicity to *Ceriodaphnia* when EDTA was added. The authors indicated that metals appear to be partially associated with observed toxicity, but did not consider metals to be the primary contributors. It should be noted that EDTA removes metals from the sample; however, it does not effectively remove anions such as selenium. Therefore, the TIE conducted does not address the potential effects from selenium exposure.

The authors noted that their findings that organic constituents were the primary contributors to toxicity of surface water in the watershed support the work by Lee and Taylor (2001).

Newport Bay

Bay et al. (2004) reported the results of an investigation of sediment contamination in Newport Bay. Sediment and water column samples were collected at 10 locations in both September 2000 and May 2001. Toxicity tests employed to various extents included the purple sea urchin (*Strongylocentrotus purpuratus*) fertilization test, the purple sea urchin embryo development test, a mysid (*Americamysis bahia*) 7-day survival and growth test, an amphipod (*Eohaustorius estuarius*) survival test, and sediment-water interface testing (using the sea urchin fertilization and embryo development bioassay). Sediment toxicity was observed at 7 of the 10 stations; however, selenium was not elevated above threshold targets and was not indicated as a potential cause of the toxicity. Based on TIE analyses, multiple toxicants of concern are present, and the effects observed were not due to naturally occurring factors such as sediment grain size or ammonia. As with the studies within the San Diego Creek watershed, toxicity is believed to be associated with organic compounds (possibly organophosphate or pyrethroid pesticides). The authors also noted that limited evidence from the studies suggest that trace metals may contribute to observed toxicity in sea urchins exposed to pore water from the upper bay. Selenium is not specifically mentioned in discussions of these potential trace metals (likely a mixture of metals).

Summary

Extensive toxicity testing has been conducted within the San Diego Creek watershed and Newport Bay, with surface water, sediment, and pore water being evaluated. These studies have used standard toxicity testing methods and sampling regimes designed to understand toxicity in both low- and high-flow conditions (i.e., dry- and wet-weather sampling). Results have indicated widespread toxicity within the watershed and the bay, and a consistent finding of the studies is that organic constituents are likely the primary contributors to the observed toxicity. To a lesser degree, trace metals were also thought to be potential contributors; however, selenium was not discussed as a chemical of concern in the bay and evidence in the watershed did not implicate selenium in the observed toxicity (i.e., selenium concentrations did not vary with toxicity).

2.4.4. Comparison to Selenium Hazard Index

Luoma and Presser (2000) briefly describe the Hazard Index approach developed by Lemly (1995 and 1996a). This systematic approach uses a scoring method developed by Lemly in which points are assigned to define the selenium hazard in specific systems. A hazard, as defined by Lemly, is a toxic threat to fish and birds that can be characterized by selenium concentrations in the environment (water and sediment) and exposure of fish and birds to that hazard (i.e., tissue concentrations). The scores represent the sum of all lines of evidence (water sampling, sediment, invertebrates, fish, and bird eggs). Lemly (1995 and 1996a) then assigned certain point ranges to five categories of hazard as follows:

- **High Hazard (16 to 25 points):** Imminent, persistent threat sufficient to cause complete reproductive failure in most species of fish and birds.
- **Moderate Hazard (12 to 15 points):** Persistent toxic threat sufficient to substantially impair, but not eliminate reproductive success.
- **Low Hazard (9 to 11 points):** Periodic or ephemeral toxic threat that could marginally affect reproductive success of some sensitive species, with most species being unaffected.
- **Minimal Hazard (6 to 8 points):** No toxic threat identified, but concentrations of selenium are slightly elevated compared to uncontaminated reference areas.
- **No Hazard (5 points):** Selenium concentrations are not elevated in any ecosystem component compared to reference areas.

This hazard index approach will be applied to the Newport Bay watershed to determine areas of potential toxic threat to fish and birds. Currently, the State Water Resources Control Board is developing a systematic approach to using multiple lines of evidence to assess both direct impacts to biological communities and indirect effects that occur through bioaccumulation processes under their Sediment Quality Objectives project. Other approaches such as this for evaluating toxic risks to fish and birds will be employed if determined to be applicable to the watershed. The determination of which level of risk is acceptable will be addressed in the management plan for the watershed.

3. 3. REFERENCES

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