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Modeling of Selenium for the San Diego Creek Watershed and Newport Bay, California

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Abstract

The San Diego Creek watershed and Newport Bay in southern California are contaminated with selenium (Se) as a result of groundwater associated with urban development overlying a historical wetland, the Swamp of the Frogs. The primary Se source is drainage from surrounding seleniferous marine sedimentary formations.   An ecosystem-scale model was employed as a tool to assist development of a site-specific Se objective for the region. The model visualizes outcomes of different exposure scenarios in terms of bioaccumulation in predators using partitioning coefficients, trophic transfer factors, and site-specific data for food-web inhabitants and particulate phases. Predicted Se concentrations agreed well with field observations, validating the use of the model as realistic tool for testing exposure scenarios. Using the fish tissue and bird egg guidelines suggested by regulatory agencies, allowable water concentrations were determined for different conditions and locations in the watershed and the bay. The model thus facilitated development of a site-specific Se objective that was locally relevant and provided a basis for step-by-step implementation of source control.

Introduction

Understanding the biotransfer of selenium (Se) is essential for evaluating the effects of Se on ecosystem resources. The linked approach presented in the San Francisco Bay-Delta Selenium Model (Presser and Luoma, 2006) considers progressive modeling of Se through water-column loads, concentrations, and speciation; particulate matter transformation and bioavailability; the biodynamics of bioaccumulation in prey; and trophic transfer to predators. This approach can conceptualize and model Se exposure through site-specific food webs and determine the vulnerability of predator species in an ecosystem. This approach also can be used to generate forecasts of how Se moves through a watershed and estuary based on selected management and regulatory options.

Groundwater- and wastewater-related discharges of Se within the San Diego Creek watershed have the potential to adversely affect surface waters and, hence, habitats within the watershed and Newport Bay (fig. 1) (U.S. Environmental Protection Agency, 2002). In 2004, the California Santa Ana Regional Water Quality Control Board issued a revised National Pollutant Discharge Elimination System permit regulating groundwater-related discharges in the watershed (California Santa Ana Regional Water Quality Control Board, 2004). This specific revised regulatory approach addressed (1) the presence of Se and nitrogen and (2) the ability to comply with established Total Maximum Daily Load requirements for impaired water bodies (that is, San Diego Creek and Newport Bay) (U.S. Environmental Protection Agency, 2002). This action initiated an alternative compliance approach allowing stakeholders to participate in Work Groups to develop and implement a comprehensive Work Plan to address Se and nitrogen. This process included Federal agencies (U.S. Environmental Protection Agency, U.S. Fish and Wildlife, U.S. Geological Survey), State and County agencies (California State and Regional Boards; California Department of Fish and Game; County of Orange), and three consulting groups (CH2M Hill, RBF Consulting, and Larry Walker Associates) working cooperatively as the Resource and Regulatory Agency Group with the regulated community to develop a site-specific Se objective to integrate into a watershed scale management strategy for Se (California County of Orange, 2006a; Larry Walker Associates and CH2M Hill, 2007; California Nitrogen and Selenium Management Program, 2006a). A primary task included in the development of the site-specific Se objective was the adaptation of the San Francisco Bay-Delta Selenium Model to the San Diego Creek watershed and Newport Bay. The modeling would translate selected tissue guidelines for predators (that is, whole-body fish tissue and bird egg tissue) to dissolved Se concentrations at chosen sites in the watershed. The dissolved Se concentrations would then facilitate calculation of Total Maximum Daily Load Se requirements for the watershed (U.S. Environmental Protection Agency, 2002).

This report is supplemental to the larger effort of justifying, deriving, and implementing a site-specific Se objective for San Diego Creek watershed and Newport Bay (California Santa Ana Regional Water Quality Control Board, 2004). In that regard, this report is written mainly for a specific audience that has considerable knowledge of the watershed and has participated in Resource and Regulatory Agency Group and Work Group meetings from 2007 to 2009. In addition to this project report, a report is planned that further details and justifies the approach for ecosystem-scale modeling of Se.

This report (1) designs conceptual models for the San Diego Creek watershed and Newport Bay; (2) derives and justifies partitioning coefficients (K_ds) and trophic transfer factors (TTFs) used in modeling of the watershed and bay; (3) models different food-web scenarios to elucidate Se exposure within the watershed and bay; and (4) compares predicted Se concentrations to modeled Se concentrations (that is, validation). The work presented here shows the nature of a cooperative iterative process resulting in site-specific regulation and the evolution of our modeling effort. During this time, additional field data became available, data gaps were addressed, feedback was given, guidelines were developed, and revised exposure scenarios were completed. Thus, this report, in addition to illustrating modeling of Se for the watershed and bay, serves as a record to support decision-making within the larger group of resource and regulating agencies.

From a scientific perspective, this watershed-scale project illustrates the importance of ecosystem knowledge, especially ecology, for successful Se modeling.

Conceptual Models

A generalized schematic of the San Diego Creek watershed and Newport Bay is presented in Figure 1. The watershed is in an urban setting that is intensively developed (93 percent urban uses; 7 percent agricultural uses, including plant nurseries). Newport Bay is an important southern California estuary that is an ecological reserve in the upper portion and a developed marina for recreational boating and fishing in the lower portion. Figure 1 shows the boundaries of historical marshes (Swamp of the Frogs and an ephemeral lake), and these areas overlay aquifers containing the most elevated Se concentrations (Hibbs and Lee, 2000; Meixner and others, 2004). Geologic Se sources are implicated for the watershed including the surrounding Monterey Formation (Piper and Isaacs, 1994). Ninety-six percent of Se loading is estimated to be from groundwater sources in the watershed (California Nitrogen and Selenium Management Program, 2006b; 2009). Drains and drainage channels are important parts of the hydrology of the watershed because of the presence of a high ground water table (Hibbs and Lee, 2000; Meixner and others, 2004).

Sites for modeling (Larry Walker Associates Inc. and CH2M Hill, 2007) within the San Diego Creek watershed and Newport Bay include:

- marsh drains (drains within the area historically designated as the Swamp of the Frogs);
- non-marsh drains (drains outside the area of the historical swamp);
- upper and lower San Diego Creek (SDC);
- upper and lower Peters Canyon Wash (PCW);
- Irvine Ranch Water District (IRWD) off-channel wetlands;
- University of California at Irvine (UCI) off-channel wetlands; and
- Upper and Lower Newport Bay.

Some data exist for other freshwater drainages to the bay [for example, Santa Ana Delhi Channel (SADC), Big Canyon Wash], but these sites are not included in the final exposure analysis.

Aquatic habitat categories within the area are: riparian channels and pools; control basins; freshwater wetlands; salt marsh; tidal mudflat; estuarine open-water; and marine open-water. The quality of the habitats varies, as does the potential for Se interaction (for example, low habitat value and high Se exposure in some marsh drains). Many of the habitat components are highly engineered and managed to serve several purposes, including treatment for nitrogen and phosphorus and sediment control (for example, in-channel or off-channel wetlands; detention basins in lower San Diego Creek).

The Upper Newport Bay Ecological Reserve and the bay itself (fig. 1) are important stopovers for birds on the Pacific Flyway. Threatened or endangered bird species include the light-footed clapper rail (*Rallus longirostris levipes*), California brown pelican

(*Pelecanus occidentalis californicus*), and California least tern (*Sterna antillarum browni*) (Sutula and others, 2005; Allen and others, 2008). Bird species of concern in California are osprey (*Pandion haliaetus*), double-crested cormorant (*Phalacrocorax auritus*), elegant tern (*Thalasseus elegans*), black skimmer (*Rhynchops niger*), and California gull (*Larus californicus*). Forage fish species that serve as food for birds include killifish, goby, juvenile halibut, sculpin, and topsmelt (Allen and others, 2004). Larger predatory fish species include sea basses, halibut, sand bass, croaker, and jacksmelt. Shellfish sampling of bivalves showed 24 species of bivalves, with the lower bay supporting more species (California County of Orange, 2004). However, lack of previously available commercial species has deterred studies to evaluate the suitability of existing bay habitats and water quality for renewal of a shellfish industry. Several organic chemicals, including modern pesticides (diazinon, chlorpyrifos) and legacy pesticides (DDT, Chlordane), as well as heavy metals (cadmium, copper, lead, zinc, and mercury) also are of concern in the watershed and bay and may have affected the status of specific food webs and their inhabitants (U.S. Environmental Protection Agency, 2002).

Conceptual Se models for the San Diego Creek watershed and Newport Bay are based on the approach of Presser and Luoma (2006) (figs. 2-4). Important components of food webs identified from site-specific monitoring data (CH2M Hill, 2008a) for the freshwater portions of the watershed are:

- invertebrates: aquatic insect, crayfish, clam, snail, worm, leech.
- fish: minnow, sunfish, carp shiner, crappie, catfish, bass, mosquitofish.
- birds: avocet, stilt, rail, killdeer, coot, mallard, grebe.

Important components of food webs identified from site-specific monitoring data (CH2M Hill, 2008a) for the estuarine and marine portions of bay are:

- invertebrates: amphipod, isopod, clam, mussel, crab, snail.
- fish: mullet, killifish, goby, anchovy, sandbass, turbot, halibut, sculpin, perch, topsmelt.
- birds: avocet, stilt, rail, killdeer, tern, skimmer.

Some species not represented in the collected species (for example, polychaetes) were modeled because of implications for past and future food webs.

Datasets compiled for modeling are food-web-specific and include Se data for the water column (dissolved or total Se); particulate phases; invertebrates; fish (whole-body); birds (egg); and, when available, dissolved Se speciation and salinity (CH2M Hill, 2008a). These datasets are limited to data that are temporally and spatially matched [that is, datasets gathered across media (water, particulate material, invertebrates, fish and/or bird tissue) and during a constrained time period]. Summaries of the data are presented in this report, with extensive documentation available in the spreadsheet datasets that are part of the site-specific Se objective process (CH2M Hill, 2008a). Data are sorted according to seasonal conditions (wet season, November through April, and dry season, May through October). However, the small number of data for prey and predators precluded conclusions based on season. All solids data are given in dry weight (dw).

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Partitioning Coefficient (K_d)

San Diego Creek Watershed

Partitioning of Se between water and particulate material is a dynamic biogeochemical process. Because of the biology involved, it is complex to model (that is, geochemical modeling misses major biological processes). At any point in time and space, Se partitioning can be described by a distribution coefficient, which is the ratio

K_d = Se concentrations in particulate (µg/kg dw) / Se concentrations in water (µg/L).

Note that particulate Se concentrations are usually expressed as µg/g dw. These units must be converted to µg/kg dw to make the particulate concentrations comparable to water concentrations. Presser and Luoma (2006) explained this coefficient in detail and presented data from the literature showing the wide range of distribution coefficients (K_d's) that occurred in different environments. They recognized that the use of K_d is an operational, descriptive choice for characterizing Se dynamics in an environment. As a practical measure K_d is very useful, but there are limits to its interpretation in terms of describing and quantifying phase transformation processes (Presser and Luoma, 2006).

A major factor determining the magnitude of the partitioning coefficient is Se speciation in the water column (Presser and Luoma, 2006). Dissolved Se can exist as selenate, selenite, and organo-Se. Selenium speciation also differs in nature with the character of the input to a water body and the residence time in the water body. For example, Se often enters a stream (for example, San Diego Creek) as selenate. If that stream flows into a wetland and is retained in a wetland (that is, in-stream water becomes off-stream water) with sufficient residence time, then recycling of Se may occur. During recycling, some selenate is taken up by bacteria and/or plants and converted to selenite and organo-Se. These reduced species then are released back to the water as these organisms die and decay. The more recycling, the more selenite and organo-Se are produced. Neither of the latter forms can be re-oxidized to selenate; that reaction takes hundreds of years (Cutter and Bruland, 1984). Therefore, the net outcome of recycling in a watershed is a gradual buildup of selenite and organo-Se in the water. This process is evidenced in the San Diego Creek watershed by a small increase in selenite (21 to 25 percent) toward the downstream end of the system, 39-100 percent selenite in watershed wetlands, and as much as 78 percent selenite in the estuary (table 1).

Reactions between particles and dissolved Se are dominated by biological uptake into bacteria, plants, and their decaying debris termed detritus. Selenate is the least reactive of the three forms of dissolved Se in generating particulate material. Thus, if selenate is the only form of Se, then the K_d tends to be low. This condition reflects low Se concentrations on particulate material compared to Se concentrations in the water column. As selenite concentrations increase (even if that increase is small) the ratio begins to increase. In the case here, as the San Diego Creek watershed changes from freshwater to the saline water of the estuary and bay, residence time increases, recycling increases, and eventually the ratio of particulate to dissolved Se can be extremely high as Se is stripped from the water column with increasing effectiveness.

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Presser and Luoma (2006) discussed several studies that supported the link between speciation and partitioning coefficient; however, several additional studies are included in this report. Calculations using data from laboratory microcosms and experimental ponds show speciation-specific K_ds of 140-493 for selenate; 720-2,800 when an elevated proportion of selenite exists; and 12,197-36,300 for 100-percent dissolved seleno-methionine uptake into algae or periphyon (Besser and others, 1989; Graham and others, 1992; Kiffney and Knight, 1990). These ranges are consistent with the general ranges for K_d used by Presser and Luoma (2006) for modeling of the San Francisco Bay-Delta Estuary when they developed scenarios based on several possible fates for Se. These ranges also are consistent with the full range for Se in the San Diego Creek watershed and Newport Bay.

The K_d also can be influenced by the type of material in the sediment, although to a lesser degree than by speciation. For example, field data for Luscar Creek in Alberta, Canada, show a hierarchy of Se concentrations: 2.4 µg/g dw in sediment, 3.2 µg/g dw in biofilm, and 5.5 µg/g dw for filamentous algae (Casey, 2005). Using these concentrations with a field-measured dissolved Se concentration of 10.7 µg/L yields K_ds of 224, 299, and 514 respectively, with an average K_d of 346. Similarly, field data for a slough tributary to the San Joaquin River, California, show a hierarchy of Se concentrations: 0.47 µg/g dw in sediment, 2.4 µg/g dw in algae, and 7.9 µg/g dw in detritus (Saiki and others, 1993). Using these concentrations with a field-measured dissolved Se concentration of 13 µg/L yields K_ds of 36, 185, and 608 respectively, with an average K_d of 276.

Interpretation of particulate Se concentrations should take into consideration, where possible, the nature of the particulate material. Bed sediments are the least desirable choice for calculating K_d, especially if the sediments vary from sand to fine-grained material among the samples. Sandy sediments dilute concentrations with a high mass of inorganic material and may yield K_ds that are anomalously low. On the other hand, bed sediments samples are the most traditional type of sample to collect; and Se concentrations in bed sediment are commonly all that are available. In that case, these data are used for determination of K_d. Further operational choices include comparison of one consistent type of material among locations or comparison of an average of the different types of materials (that is, all relevant particulate phases). In practical terms however, modelers usually have to work with the particulate Se data that are available and try to find ways to both minimize the influences caused by particle type and capture the influences of changes in speciation. This is the approach taken below.

Several approaches are possible in choosing a K_d(s) for the San Diego Creek watershed. The dataset for Se concentrations in the water column is extensive, but a smaller dataset exists for particulate Se concentrations (CH2M Hill, 2008a). Table 1 is a summary of total water-column Se concentrations and the percentages of dissolved selenite for the watershed during the dry season. The datasets for water and sediment data pairs were more numerous for the dry season than for the wet season. Table 2a shows a summary of available Se concentrations for bed sediment and algae samples collected in the same place and at the same time as the water-column samples (that is, matched samples). The 75th percentile values for all data collected at each of the sites also are shown. Use of a 75th percentile value was chosen by the Resource and Regulatory Agency Group as a

useful statistical representation for the data. The location-specific K_ds are calculated from these data and are shown in table 2a. Table 2a was assembled at the request of the Resource and Regulatory Agency Group for the purpose of illustrating the basis for decisions (and the uncertainty around those decisions) concerning K_ds for the watershed. Table 2a is complex, but the compilation is intended to show all the available data and the limitations of the datasets for particular sites.

The K_ds for different environments in the San Diego Creek watershed vary from <100 to a maximum of 938, averaging 241 (table 2b). The UCI marsh is a consistent exception from the rest of the watershed, with K_ds from 656 – 939, averaging 791. Excluding UCI marsh, the range is 19 to 444, averaging 168 across the entire creek. Thus, the variability (based on a coefficient of variation) in the K_d in this area is about twofold. The 75th percentile for all values (excluding UCI marsh) is 238. The type of particulate materials used (for example, sediment or algae) has a small influence on K_d in this dataset. Differences are not large between K_ds determined from matched data-pairs (particulate and water samples collected in the same place and at the same time) and K_ds calculated from the 75th percentile of all available water and sediment data (where enough sediment data are available to do that calculation). The greatest differences in Kds, however, are due to the inherent spatial variability in the data (table 2).

Choices for K_d used in freshwater modeling (shown later in tables 18-22) are:

1. A choice for K_d of approximately 200 would illustrate a representative freshwater average scenario. This choice of K_d reflects the mean (168) and 75th percentile (238) K_ds for the San Diego Creek watershed. Predictions using this K_d would represent water-column Se concentrations if conditions in the watershed stayed much like they are now.

2. A more environmentally conservative approach is illustrated using the 75th percentile of all K_dS (approximately 400). Predictions using this K_d would represent water-column Se concentration if conditions in the watershed change, for example, to allow more recycling. Use of this environmentally conservative K_d would be desirable to assure the greatest likelihood of remaining below fish-tissue guidelines within the entire watershed.

3. An alternative approach would be to assume that any areas that behaved like the UCI wetlands must be protected. In that case, a K_d of 800 could be used in modeling.

Newport Bay

Table 3 shows a summary of dissolved Se concentrations for Newport Bay as a function of salinity (parts per thousand, ppt) and the percentage of selenite as a fraction of the dissolved Se. Concentrations decline dramatically between the mouth of San Diego Creek and the lower bay. Dissolved Se concentration data in a transect from near the mouth of the estuary at San Diego Creek into Upper Newport Bay (table 4) were used to predict the Se concentration at the mouth of the estuary (at 0 ppt salinity) (fig. 5; table 3). The extrapolation of the dissolved Se concentration from a salinity of 15.1 ppt to a salinity of

0 ppt is based on Se being conservative (that is, no loss into other phases of the environment). Table 4 also shows the results of Se analysis of suspended particulate samples for the upper bay taken at the same time as the dissolved samples. The K_ds calculated from the matched dissolved and particulate Se concentrations increase from 107 in the landward-most sample to as high as 578 and 776 seaward. One choice for a K_d for modeling the upper bay is the mean of these values: 264. Another alternative is the 75th percentile value: 353.

Table 5 shows the mean of 11 samples of dissolved and bed-sediment Se concentrations collected at different harbors of Newport Bay, most of which are in the lower bay. The locations closest to where San Diego Creek enters the upper bay (Newport Dunes and Bayside DeAnza) had the lowest Se concentrations in sediment and the highest dissolved Se concentrations for this dataset. The most enclosed location (Harbor Towers), which is likely to have the poorest circulation and longest residence, had the highest Se concentrations in sediments and low dissolved Se. These patterns suggest that biogeochemical processes progressively transform Se to particulate forms as the contaminants are transported seaward and residence time allows longer reaction times. The distribution also could reflect some transport seaward of fine-grained sediments from the watershed. Whatever the processes involved, most of the Se coming from the watershed is trapped in these harbors. K_ds also increase dramatically in these environments (from approximately 7,000 to 43,000). Unfortunately no data are available to track Se concentrations on suspended particulate concentrations in the water column, making it difficult to draw conclusions about how tightly the water-column community of invertebrates, fish, and birds is linked to these contaminated sediments. Modeling for the bay depends on particulate Se data and an assumption that bed-sediment Se concentrations are linked to the Se concentrations in invertebrates, fish, and birds in the system. Choices for estuary and bay modeling shown later employ K_ds of 200, 1,000, 10,000 and 20,000 to represent the various conditions from the upper bay to the most isolated harbors.

Trophic Transfer Factors (TTFs)

Traditional models for aquatic systems attempt to quantify the linkage between Se concentrations in invertebrates, fish, and aquatic birds and those in the environment. The traditional approach was to employ a bioconcentration factor (BCF), which is the ratio between Se accumulated by an organism from water and Se concentrations in the water; or a bioaccumulation factor (BAF), which is the ratio between the concentration accumulated by the animal from all sources (for example, in the field) and the concentration in the water column. It is well recognized that BCFs and BAFs are extremely variable among circumstances and are not constants (McGeer and others, 2003; DeForest and others, 2007). The latter means that both factors can change as Se concentrations change, even if all other conditions are held constant. It is also widely recognized that this approach is not very useful for understanding Se exposures because it skips links among components of food webs (figs. 2-4).

Selenium trophic transfer factors (TTFs), on the other hand, take account of the well-established principle that Se is bioaccumulated almost entirely from the food an animal

eats (Luoma and others, 1992; Presser and Luoma, 2006). In addition, the extent of bioaccumulation (that is, the concentration achieved by the organism) is driven by physiological constants that are specific to each species (Luoma and Rainbow, 2005). Experimental protocols are now well developed for defining those constants. The constants are assimilation efficiency (AE), ingestion rate (IR) and the rate constant that describes Se excretion or loss from the animal (k_e). In the absence of rapid growth, the species-specific potential for an organism to bioaccumulate Se is

$$TTF = [(AE)(IR)]/k_e.$$

as defined by Reinfelder and others (1998) and reviewed by Wang (2002). If field data are available, derivation is from matched data-pairs using the equation

$$TTF = C_{animal} \div C_{diet}$$

Invertebrates

TTFs from kinetic experiments

Table 6 shows a summary of Se TTFs determined in robust kinetic experiments over the past decade for a variety of marine invertebrate taxa and the freshwater zebra mussel. The clam *Corbicula fluminea* can exist in both freshwater and marine environments. The table also illustrates the degree of variability among different determinations of TTF. The variability typically reflects the influences of different factors, such as food type and food availability, but also includes some influence from experiment-to-experiment variability. The variability among studies for each species is typically much smaller than the variability among species.

TTFs from field data

Selenium TTFs also can be derived from field data, using the ratio of bioaccumulated Se in the animal versus the concentration of Se in its food. Table 7 shows a summary of TTFs derived for different animal taxa from field studies for which robust data are available. Kinetic TTFs are given where appropriate for comparison. The use of these field data allows us to expand the number of taxa for which TTFs are available for modeling.

TTFs from San Diego Creek

Some data for Se concentrations in invertebrates are available from both the San Diego Creek habitat and from Newport Bay. Tables 8 and 9 show summaries of available Se concentrations for invertebrates collected in the San Diego Creek watershed and Upper and Lower Newport Bay. One way to verify if data from other locations are appropriate for use in the San Diego Creek situation is to compare TTFs from the small data set available for the local environment with those from elsewhere. Table 10 shows a comparison of the TTFs derived locally with a summary of those derived in tables 6 and 7. The local values, even though based upon a limited number of data-pairs in many cases, are comparable to the literature-derived values, verifying that studies in other

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situations are applicable to the local conditions in the San Diego Creek watershed (table 10). From these summaries, choices are possible with regard to which TTFs to use in modeling for major groups of taxa:

- Freshwater:
    - insects in general: 2.8
    - zooplankton: 1.5 (amphipod: 0.6; copepod: 2.05)
    - freshwater clams: 2.7
    - freshwater mussels: 6
- Bay
    - deposit-feeding clams: 7.4
    - marine mussels: 6
    - amphipods: 0.6
    - zooplankton: 1.5
    - polychaete worm: 4.5

Although some clams show much higher potential for bioaccumulation, this has not been verified in the field.

Fish

Table 11 shows a compilation of Se TTFs for fish derived from experimental studies and from sets of matching field data for invertebrates and fish. The average TTF for this set of data is 1.18 and the 75th percentile is 1.34. Table 12 shows a summary of available Se concentrations for fish tissue collected in the watershed. Table 13 shows the derivation of site-specific Se TTFs for fish in the watershed based on matched fish and invertebrate data. Fewer data are available for fish than for invertebrates in the watershed. The range of site-specific TTFs is 0.8 to 4.6, so choosing a Se TTF for fish of 1.1 to 1.2 would be conservative on the basis of local data. Table 14 shows a summary of available Se concentrations for fish tissue collected in the bay and calculated site-specific TTFs based on matched fish and invertebrate data. The range of site-specific TTFs is 0.62 to 1.3. Most modeling scenarios use a default TTF for fish of 1.1.

Birds

Tables 15 and 16 show summaries of available Se concentrations for bird eggs collected in the watershed and bay. Table 17 shows the laboratory data used to derive a TTF for birds for modeling. A range of 1.8 to 2.9 is shown. The toxicity endpoint for the experimental studies was reduced hatchability in mallard eggs (Ohlendorf, 2003). A TTF of 1.8, the lowest value derived from this dataset, is chosen for modeling. This choice would represent the least effective bioaccumulative potential derived from the dataset. The choice of 1.8 can be modified as part of exposure scenarios if regulating agencies such as the U.S. Fish and Wildlife Service decide to do so. The TTFs derived from experimental data may be most relevant to resident birds rather than to birds feeding in a larger range of diverse habitats. Another compilation of studies relevant to calculating TTFs for birds concluded that a TTF of 1.4 was appropriate for the watershed (CH2M HILL, 2008b).

Modeling

Scenarios

Modeling scenarios were constructed throughout the course of the development of a site-specific Se objective for the San Diego Creek and Newport Bay watershed. The generalized equations (Presser and Luoma, 2006) used for translation of tissue Se guidelines to dissolved Se concentrations are

$$C_{water} = (C_{fish}) \div (TTF_{fish}) \, (TTF_{invertebrate}) \, K_d$$

$$C_{water} = (C_{bird \, egg}) \div (TTF_{bird}) \, (TTF_{invertebrate}) \, K_d$$

Equations may be modified for more complex food webs by inserting additional TTFs. In addition to modeling scenarios chosen for illustration of specific food-web exposure in the watershed and bay, some modeling conditions were stipulated by those collaborating in the site-specific Se objective process.

A series of exposure scenarios are shown in tables 18-20 (for example, particulate to invertebrate to fish to bird; particulate to invertebrate to bird; particulate to invertebrate to forage fish to predator fish). The scenarios employ a fish-tissue target of 5.0 µg/g whole-body dw or a bird-egg target of 8.0 µg/g whole-egg dw. These targets were chosen as part of the regulatory process of the Resource and Regulatory Agency Group for the San Diego Creek watershed and Newport Bay. The Se TTF used for modeling exposure of fish is 1.1, except for mosquitofish, where a TTF of 2.2 was used. The TTF used for modeling exposure of birds is 1.8. For the watershed, aquatic insects (TTF = 2.8) were used as the selected invertebrate on which to base translation for invertebrate-eating fish or birds. Selenium TTFs for invertebrates used in modeling for the mouth of the estuary and the upper and lower bay varied from 2.05 for copepod, 4.5 for polychaete, and 7.4 for clam. Modeled K_ds were those derived previously to represent the habitats of the watershed (200-1,000) and bay (200 to 20,000). Tables 21 and 22 show requested generalized exposure scenarios for the watershed based on protecting fish or birds. Results of modeling are shown for varying K_ds, guidelines for the protection of fish and birds, and the TTFs for birds.

Modeling of the conditions and habitats of the San Diego Creek watershed and Newport Bay shows the importance of (1) wetlands within the watershed and (2) estuary interaction within the lower and upper bays in determining the fate of Se discharged within the watershed. Food-web modeling of the watershed predicts increased Se transfer from the upper watershed through lower San Diego Creek to the lower wetlands. Food-web modeling of Newport Bay predicts that if predators are limited to feeding on prey from the water column (the current main food webs), then trophic transfer will be less than if transfer is through a food web consisting of benthic predators (restored food webs).

Validation

Comparisons were made between predicted concentrations and available observed Se concentrations for invertebrate, fish, and bird species to test the validity of the selected approach and site-specific assumptions for the San Diego Creek watershed and Newport Bay (tables 23-28). In some cases, few data were available for comparison. Predicted Se concentrations were in the range of observed Se concentrations for most modeled cases. Where there were discrepancies, modeling factors were examined and redefined or it was recommended that additional data be collected to confirm modeling expectations.

Summary

Critical variables to be considered in modeling and protection of a watershed or estuary are (1) Se speciation in the water column, (2) bioavailablity of particulate material as food for invertebrates, and (3) the biodynamics of food ingestion in invertebrates, fish, and birds. Site-specific modeling of Se exposure in prey-predator pairs in the San Diego Creek watershed and Newport Bay illustrates the differences in invertebrate physiology that are propagated to higher trophic levels as a main determinant of exposure and, hence, risk. Modeling of the estuary and bay illustrates that biogeochemical processes progressively transform Se to particulate forms as the contaminants are transported seaward and residence time allows longer reaction times.

A final recommendation of a site-specific Se objective for San Diego Creek watershed and Newport Bay involves more choices than analyzed here. These choices include collaborative resolution of (1) what habitat to protect (the most sensitive part of the watershed or bay; a generalized watershed; individual components of the watershed or bay); (2) what predators and food webs to protect (endangered and threatened species; commercially valuable species; existing abundant species); (3) what parameters to use in modeling (maximums; averages; or 75th percentile); and (4) what type of guideline to adopt (fish or bird tissue; dietary; or water column). An overarching question for those confronted with protection of a watershed/estuary that is affected by a mixture of legacy pollutants, such as the San Diego Creek watershed and Newport Bay, is whether to restore the ecosystem and consider exposure scenarios based on potential future inhabitants of the ecosystems.

Acknowledgments

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Tables

Table 1. Total water-column Se concentrations and Se speciation for the San Diego Creek watershed.

location	season	75th percentile (µg/L)	mean (µg/L)	minimum (µg/L)	maximum (µg/L)	selenite (%) (selenite/dissolved Se)
Upper PCW	dry	2.5	5.0	0.1	24.7	up to 21%
Upper SDC	dry	4.6	2.9	0.7	6.1	up to 21%
Lower PCW	dry	31.0	21.8	1.6	44.0	up to 22%
Lower SDC	dry	16.0	12.3	1.2	37.5	up to 25%
IRWD wetlands	dry	15.6	11.7	4.0	16.9	up to 39%
UCI wetlands	dry	2.9	2.3	1.3	3.0	up to 100%
OTHER						
Marsh Drains	dry	24.2	14.9	0.1	162.0	
Non-Marsh Drains	dry	4.7	5.4	0.5	79.8	
SADC	dry	14.0	9.9	2.2	19.0	up to 11%
IRWD (IN)[a]	dry	19.1	12.9	4.0	20.7	
IRWD (OUT)[a]	dry	13.3	10.5	4.0	14.1	

[a] denotes location near inflow or outflow.

Table 2a. Dissolved or total water-column Se concentrations; Se concentrations in bed sediment and algae; and calculated Kds for the San Diego Creek watershed (freshwater sites). [Kds are calculated from matched (that is, temporally and spatially paired) and 75th percentile datasets when data are available. The average of the sediment and algae Se concentrations are preferentially used, if available, to calculate Kd. Additional available data are listed in brackets ([ ]) to substantiate data ranges for sites. See additional notes in text on assemblage of table. dw = dry weight; n = number of samples.]

location, season, and speciation	water (µg/L)	bed sediment (µg/g dw)	algae (µg/g dw)	average (sediment and algae) (µg/g dw)	K_d sediment/water (µg/kg/µg/L)
Upper SDC (matched) DRY	0.79	0.2			253
Upper SDC (75th percentile) DRY	4.6	0.2 (n=1)			43
Upper PCW (matched) DRY (up to 21% selenite)	3.4 total 3.2 dissolved	0.6 0.6	1.2 1.2	0.9 0.9	264 281
Upper PCW (75th percentile) DRY	2.5	0.6 (n=1)			240
Non-marsh drains (matched)	none	none			none
Non-marsh drains (75th percentile)	4.7 DRY 3.65 WET	none			none
Marsh drain (matched) DRY	0.25-28.1 ⁣ 11.1	none	0.6 2.4 3.1 3.8 3.1		279
Marsh Drains (75th percentile)	24.2 DRY 17 WET	none			none
Lower PCW (matched) DRY (up to 22% selenite)	8.1	--- [0.86]	3.6 [2.5, 1.6]		444 based on algae
Lower PCW (matched) WET	30		6.7		223
Lower PCW (75th percentile)	31 ALL	4.1 n=6 ALL (0.7-13.8)			132
Lower SDC (matched) (up to 25% selenite)	3.3 DRY (n=1) 29 DRY (n=1) 4.1 DRY (May) 19.2 25.3 WET (n=1) 18.4 WET (n=1)	0.2 (n=1) DRY 0.54 (n=2) DRY ⁣ 0.66 (range 0.5-1.6)[a] 2.6 (range 0.17-2.6) WET 2.6 (range 0.17-2.6) WET [3.1]	0.64 (n=1) DRY		61 19 156 34 103 141
Lower SDC 75th percentile mean	17 DRY 12.7	1.16 0.95			68 75

minimum	1.2	0.09			75
maximum	37.5	6.2			166
Lower SDC, 75th percentile	19.7 WET	1.16			59
mean	13.3	0.95			71
minimum	0.75	0.09			120
maximum	39	6.2			159
IRWD wetlands (matched) WET					
pond 1	21.1	2.3			109
pond 1 anti-predator trench	21.1	2.7			128
pond 3	20.4	4.5			221
pond 3 anti-predator trench	20.4	5.8			284
stream and riparian zone (up to 39% selenite)	(assume 21)	6.9	5.7; 9.3	7.3	348
IRWD wetlands (75thpercentle) ALL	16.0	3.72			232
IRWD wetlands IN (75th percentile) ALL (up to 9% selenite)	21.5 in				
IRWD wetlands OUT (75th percentile) ALL (up to 39% selenite)	12.3 out				
UCI wetlands (matched) (up to 100% selenite)	none				none
UCI wetlands (DRY) 75th percentile	2.77 (n=2)	2.18 (n=5)			787
mean	2.04	1.6			784
minimum	1.31	0.86			656
maximum	2.77	2.6			939
Delhi Channel (SADC) DRY (up to 11% selenite)		0.49	2.0		none
Delhi Channel (75th percentile)	15	1.23 (range 0.5-4.0)			82

[a] sand to silty-sand sample.

Table 2b. Statistics for calculated K_ds based on table 2a data.

K_d	all sites	all sites except UCI wetlands	UCI wetlands	IRWD wetlands	UCI and IRWD wetlands
mean	241	168	792	220	449
median	159	136	786	226	316
75th percentile	279	238	825	271	752
Maximum	939	444	939	348	939
Minimum	19	19	656	109	109
n (number of data points)	33	29	4	6	10

Table 3. Dissolved water-column Se concentrations and speciation for the Newport Bay estuary.

location	dissolved or range of dissolved (µg/L)	selenite or range of selenite (%)
mouth of estuary at 0 ppt	24 extrapolated (see figure 5)	
Upper Bay at 15 ppt	14.4	11
Upper Bay at 27 ppt	3.5	19
Upper Bay at 28 ppt	2.4-1.8	18-32
Upper Bay at 30 ppt	1.3-1.0	14-25
Upper/Lower Bay at 33 ppt	0.97-0.29	21-48
Lower Bay	0.15-0.11	
Lower Bay	0.08-0.06	

Table 4. Water-column and suspended particulate Se concentrations in Upper Newport Bay in a transect from the near the mouth of San Diego Creek into the upper bay to salinities of 33.1 ppt. [Calculated K_ds and percentages of dissolved selenite also are shown. ppt = parts per thousand; dw = dry weight]

salinty (ppt)	dissolved (µg/L)	total (µg/L)	particulate (µg/g dw)	K_d	% selenite (selenite/dissolved)
15.1	14.4	18.4	1.54	107	10.7
26.6	3.50	4.02	0.39	111	18.6
30.2	1.79	2.26	0.18	101	20.1
28.0	2.32	2.47	0.27	116	22.0
31.4	1.13	1.60	0.24	212	31.9
28.7	2.42	2.97	0.21	87	17.8
31.6	1.27	1.43	0.17	134	22.0
30.5	1.31	1.67	0.24	183	13.7
31.0	1.32	1.72	0.25	189	18.9
30.8	1.18	1.53	0.17	144	25.4
31.4	0.991	1.37	0.21	212	27.2
31.6	0.837	1.02	0.24	287	25.1
32.0	0.967	0.985	0.17	176	14.5
32.8	0.445	0.548	0.17	382	31.5
33.0	0.482	0.624	0.17	353	29.0
32.8	0.438	0.744	0.34	776	32.0
32.2	0.674	0.839	0.20	297	20.8
32.8	0.508	0.698	0.17	335	27.6
32.9	0.465	0.506	0.17	366	30.1
33.0	0.294	0.351	0.17	578	47.6
33.1	0.417	0.466	0.17	408	33.6
				264 mean	
				353 75th percentile	

Table 5. Water-column and sediment Se concentrations and calculated K_ds in a gradient from landward to seaward in Newport Bay. [dw = dry weight]

location (with increasing residence time)	sediment (µg/g dw)	dissolved (µg/L)	K_d
Newport Dunes	1.07	0.15	6,933
Bayside DeAnza	1.05	0.11	9,679
Bahia Corinthian	1.17	0.07	16,675
Balboa Yacht Basin	1.06	0.06	17,026
H&J Moorings	1.10	0.08	13,508
Lido Village	1.32	0.06	20,000
Lido Anchorage	1.57	0.07	25,000
Harbor Towers	2.98	0.07	42,715

Table 6. Experimental data for invertebrate physiological factors and calculated kinetic TTFs for invertebrates.

species	AE	IR	ke	TTF (AE X IR/ke)	Reference
Marine Environments					
copepod (*Acartis tonsa*)	0.97	0.42[a]	0.13[b]	3.1	Fisher and Reinfelder, 1991
copepod (*Temora longicornis*)	0.55	0.42	0.155	1.5	Wang and Fisher, 1998
copepod (*A. tonsa; T. longicornis*)	0.8	0.42[a]	0.19	1.8	Wang and othersl., 1996a
copepod (*Oithona; Limnoithona; Tortanus; Acartia; T. longicornis*)	0.50	0.42	0.155	1.35	Schlekat and others, 2004
mysid (*Neomysis mercedis*)	0.61-0.73	0.45	0.25	1.1-1.3	Schlekat and others, 2004
amphipod (*Leptocheirus plumulosus*)	0.45	0.20	0.15	0.6	Schlekat and others, 2004
clam (*Corbula amurensis*)	0.45-0.80	0.25	0.025	4.5-8.0	Schlekat and others, 2002
clam (*C. amurensis*)	0.36-0.54	0.25	0.025	3.6-5.4	Lee and others, 2006
clam (*Corbicula fluminea*)	0.29-0.81	0.05	0.010	1.45-4.05	Lee and others, 2006
clam (*Macoma balthica*)	0.22-0.86	0.25	0.012[c]	11.2 (using mean AE)	Luoma and others, 1992
clam (*M. balthica*)	0.54 (mean)	0.25	0.030[d]	4.5	Luoma and others, 1992
clam (*Ruditapes philippnarum*)	0.52-0.70	0.25[a]	0.013[e]	10-13.5	Zhang and others, 1990
clam (*Mercenaria mercenaria*)	0.92	0.25[a]	0.010[f]	23	Reinfelder and others, 1997
oyster (*Crassostrea virginica*)	0.45-0.70	0.25[a]	0.069[g]	1.6-2.5	Reinfelder and others, 1997
oyster (*Crassostrea rivularis*)	0.55	0.45			Ke and Wang, 2001
oyster (*Saccostrea glomerata*)	0.45	0.32			Ke and Wang, 2001
mussel (*Mytilus edulis*)	0.31	0.27	0.022	3.8	Wang and others, 1996b
mussel (*M. edulis*)	0.72	0.27	0.022	8.8	Reinfelder and others, 1997
barnacle (*Balanus amphitrite*)	0.63-0.79	0.40	0.014	18-22.6	Wang and others, 1999
barnacle (*Elminus modestus*)	0.34-0.74	0.40	0.0137	9.9-21.6	Rainbow and Wang, 2001
Freshwater Environments					
Species	AE	IR	ke	TTF (AE X IR/ke)	Reference
zebra mussel (*Dreissena polymorpha*)	0.28-0.46	0.42	0.026	4.5-7.4	Roditi and Fisher, 1999
clam (*Corbicula fluminea*)	0.29-0.81	0.05	0.010	1.45-4.05	Lee and others, 2006

[a] assumed IR

[b] calculated from 5.25 day half-life

[c] chosen from Fowler and Benayoun, 1976a; Zhang and others, 1990; and Okazaki and Panietz, 1981

[d] calculated from 23 day half-life [efflux (/d) = 0.69/half-life (d)], Reinfelder and others, 1997

[e] calculated from 52 day half-life

[f] calculated from 70 day half-life

[g] calculated from 10 day half-life

Table 7. Field-derived TTFs for invertebrates from field datasets (temporally and spatially matched data-pairs), with experimentally derived TTFs given for comparison

invertebrate	kinetic TTF	field TTF	reference
Freshwater			
amphipod		0.94	Birkner, 1978; Saiki and others, 1993
zooplankton		1.5	Saiki and others, 1993
mayfly		2.7	Casey, 2005
caddisfly		3.2	Casey, 2005
cranefly		2.3	Casey, 2005
stonefly		2.6	Casey, 2005
all flies composite		3.2	Harding and others, 2005
damselfly		2.6	Birkner, 1978
midge (chironomid)		2.7	Birkner, 1978; Saiki and others, 1993
corixid (waterboatman)		2.14	Birkner, 1978
crayfish		1.5	Birkner, 1978; Saiki and others, 1993
daphnia		1.9	Besser and others, 1989
zebra mussel (*D. polymorpha*)	4.5-7.4		Roditi and Fisher 1999
clam (*C. fluminea*)	1.5-4.1		Lee et al 2006
Marine/Estuarine			
amphipod	0.6		Schlekat and others, 2004;
copepod	1.35		Schlekat and others, 2004
euphausiid		1.3	Fowler and Benayoun 1976b
mysid	1.3		Schlekat and others, 2004;
brine shrimp adult		4.2	Marden, 2008
brine shrimp nauplius		2.6	Marden, 2008
brine shrimp cysts		2.2	Marden, 2008
brine fly adult		1.8	Cavitt, 2007; Wurtzbach, 2007
brine fly larvae		1.5	Cavitt, 2007; Wurtzbach, 2007

Table 8. Invertebrate Se concentrations for the San Diego Creek watershed. [Means and ranges or values (if only two values are available) are shown. dw = dry weight; n = number of samples.]

species	Upper SDC and PCW	Marsh Drains	Lower SDC (DRY)	Lower PCW	IRWD wetlands	UCI wetlands
invertebrate (µg/g dw)						
zooplankton					6.8 (n=1)	
amhipod				8.7 (n=1)		
midge larvae (chironomid)				26.7 (8.1, 45.3) (n=2)	11 (8.4-15.7) (n=3)	
waterboatman (corixid)			7.5 (2.3-13.6) (n=4)		11.6 (1.8-23.6) (n=5)	
scud		2.7 (n=1)				
snail	1.4 (1.2, 1.7) (n=2)		4.9 (n=1)	7.3 (n=1)	5.3 (n=1)	
crayfish		4 (2.6-4.9) (n=3)	5.8 (n=1)	10.7 (n=1)	12.1 (8.5-15) (n=4)	
dragonfly (nymphs or larvae)				12.6 (n=1)	10.2 (12.5, 7.8) (n=2)	5.6 (3.2, 7.9) (n=2)
clam (Corbicula if freshwater)			7.5 (6.1-8.5) (n=9)		7.6 (n=1)	
clam (transplanted)			5.4 (n=1)	5.2 (n=1)		
backswimmer						4.2 (n=1)
worm				14.9 (n=1)		
leech				20.9 (n=1)		

Table 9. Invertebrate Se concentrations for Newport Bay. [Means and ranges are shown. dw = dry weight; n = number of samples.]

species	Upper Bay (µg/g dw)	Lower Bay (µg/g dw)
amphipod	4.8	none
isopod	8.4 (6.5 - 10.4)	
bivalve	6.1 (4.8 - 7.8)	
clam	2.9 (2.0 - 3.8)	
crab	6.1(2.5 - 8.0)	
snail	6.2 (2.3 - 12.0)	
mussels	4.4 (4.1, 4.7)	
transplanted mussels	3.9 (2.7 - 5.3)	

Table 10. Selected particulate Se concentration (see particulate Se concentration data in CH2M Hill, 2008a, matched and 75th percentile concentrations) and a comparison of calculated invertebrate TTFs for the San Diego Creek watershed and invertebrate TTF derived from the literature. [Means and ranges are shown. Two TTFs are calculated if two particulate Se concentrations were available or chosen as representative of a site. See table 8 for invertebrate Se concentrations use in calculations of TTF. dw = dry weight; n = number of samples; NA = not available.]

	Upper SDC and PCW	Marsh Drains	Lower SDC	Lower PCW	IRWD wetlands	UCI wetlands	San Diego Creek watershed (field average by invertebrate species)	other studies (by invertebrate species) (See tables 6 and 7 for data and references)
particulate Se (µg/g dw)	0.9 or 0.4	2.6	2.8 or 1.2	4.1 or 3.2	5.3 or 3.7	2.2	NA	NA
TTF-zooplankton					1.3 or 1.8 n=1		1.6	1.5 freshwater zooplankton composite; 1.4 copepod; 1.3 euphausiid; 1.2 mysid 1.9 daphnia
TTF-amphipod				2.1 or 2.7 n=1			2.4	0.6 marine 0.94 freshwater
TTF- chironomid				2.0 or 2.5 n=1	2.1 or 3.0 n=3		2.4	2.7
TTF-corixid			2.7 or 6.2 n=4		2.2 or 3.1 n=5		3.6	2.1
TTF-scud		1.0 n=1					1.0 n=1	1.4 copepod; 1.3 euphausiid; 1.2 mysid; 1.9 daphnia
TTF-snail	5.6 or 3.5 n=2		1.8 or 4.1 n=1	1.8 or 2.3 n=1	1.0 or 1.4 n=1		2.7	
TTF-crayfish		1.5 n=3	2.1 or 4.8 n=1	2.6 or 3.3 n=1	2.3 or 3.3 n=4		2.8	1.5 freshwater
TTF-dragonfly (nymphs/ larvae)				3.1 or 3.9 n=1	1.9 or 2.8 n=2	2.5 n=2	2.8	2.8 all insects
TTF-clam (*Corbicula*)			2.7 or 6.2 n=9		1.4 or 2.1 n=1		3.1	2.7*Corbicula*
TTF-clam (transplanted)			1.9 or 4.5 n=1	1.3 or 1.6 n=1			2.3 n=1	
TTF-backswimmer						1.9 n=1	1.9 n=1	2.8 all insects
TTF-worm				3.6 or 4.6 n=1			4.1 n=1	
TTF-leech				5.1 or 6.5 n=1			5.8 n=1	

Table 11. Experimentally or field derived TTFs for fish. [Matching field datasets (temporally/spatially matched data-pairs) are used in the derivation. Unless noted, transfer is from invertebrate to fish.]

species	kinetic TTF	field or lab TTF	experimental physiological factors	reference
mangrove snapper	1.1		ke 0.031; IR 5%; 69% AE)	Xu and Wang, 2002
juvenile striped bass	0.89		ke 0.08; IR 17%; 42% AE)	Baines and others, 2002
mudskipper	0.84		ke 0.019; IR 5%; 32% AE)	Ni and others, 2005
smooth toadfish	0.80		ke 0.015-0.032; IR, 7-10%; AE 24%)	Alquezar and others, 2008
fathead minnow[a]	1.0[b]		ke 0.025; assumed IR 5%; AE 50%)	Bennett and others,1986
fathead minnow adult	0.71-1.8[b]		ke 0.014;assumed IR 5%; AE 20-50%	Bertram and Brooks,1986
bluegill (fry/juvenile)[a]	0.51[b]		ke 0.035; assumed IR 5%; AE 36%)	Besser and others, 1993
bluegill (fry/juvenile)	0.61[b]		ke 0.041; assumed IR 5% AE 50%)	Cleveland and others, 1993
bluegill (juvenile)		1.15 (lab)		Lemly, 1993
bluegill		1.06		Saiki and others, 1993
white sturgeon		range 1.0-1.7		Presser and Luoma, 2006
mosquitofish		0.71-1.8 (average 1.2)		Saiki and others, 1993
mosquitofish		1.3		Saiki and others, 2008
largemouth bass		1.1; 0.95 (average 1.0)		Saiki and others, 1993
sailfin mollie		1.4		Saiki and others, 2008
rainbow trout		0.91; 0.71; 1.1; 0.96 (average 0.91)		Casey, 2005
rainbow trout		1.04		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
cutthroat trout		1.0		McDonald and Strosher, 1998
cutthroat trout from dace		0.87; 0.99 (average 0.93)		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
cutthroat trout from sculpin		0.95; 1.0 (average 0.98)		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
cutthroat trout		0.97; 1.53 (average 1.25)		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
brook trout		0.77		Hamilton 2004a,b;2005
brown trout		1.45; 1.18 (average 1.32)		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
sculpin		1.23; 1.66 (average 1.45)		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
dace		1.41; 1.65 (average 1.53)		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
chub		1.03; 1.38 (average 1.21)		Greater Yellowstone Coalition, 2005; 2006; Hamilton and Buhl 2004, 2005; Hamilton and others, 2004
shiner		1.5		Greater Yellowstone Coalition 2005; 2006
whitefish		1.3		Greater Yellowstone Coalition 2005; 2006
sucker		0.97		Greater Yellowstone Coalition 2005; 2006

[a] rotifer to larval fish microcosm or experimental microcosm

[b] with assumptions

Table 12. Fish Se concentrations for the San Diego Creek watershed. [Means and ranges by species are shown. dw = dry weight; n = number of samples.]

species	Upper SDC (µg/g, whole-body, dw)	Marsh Drains (µg/g, whole-body, dw)	Lower SDC (µg/g, whole-body, dw)	Lower PCW (µg/g, whole-body, dw)	IRWD wetlands (µg/g, whole-body, dw)	UCI wetlands (µg/g, whole-body, dw)
mixed fish	5.8 n=1		5.5 (2.4-9.0) n=3		13 n=1	
fathead minnow			9.0 (8.9-9.1) n=3	6.5 n=1		
bluegill			9.1 (5.6-12.7) n=2			
carp			9.3 (5.7-14.5) n=4		19 (dead fish filet) n=1	
red shiner			7.9 (7.4-8.5) n=2	6.3 n=1		
black crappie			6.7 n=1			
catfish			2.4 (2.2-2.7) n=2			
mosquitofish		12.5 n=1	17 n=1	21 n=2 (12.1, 29.9)	10.1 (1.3-18.9) n=10	5.8 (5.6-6.0) n=2

Table 13. Invertebrate and fish Se concentrations for San Diego Creek watershed and derivation of watershed-specific TTFs for fish. [For Se concentrations, means and ranges are shown. dw = dry weight; wb = whole-body; n = number of samples; avg = average.]

location and speciation	food web	observed Se in invertebrate (µg/g dw)	observed Se in fish (µg/g wb, dw)	watershed-specific TTF	invertebrate TTF source
Upper SDC and PCW (up to 21% selenite)	sediment> invertebrate> fish	1.4 snail n=2 5.8 tadpole composite	no fish		snail=mollusk= corbicula =2.8
Non-marsh drains					If clam, 2.8
Marsh drains	sediment> invertebrate> fish	2.7 scud n=1 4.0 crayfish n=3	12.5 mosquitofish n=1	12.5 mosquitofish /2.7 amphipod=4.6 12.5 mosquitofish /4 crayfish=3.1	crayfish=1.6; scud=amphipod= 0.9 average=1.3
Lower PCW (up to 22% selenite)	sediment> invertebrate> fish	8.7 amphipod, n=1 27 midge (8.1; 45) n=2 7.3 snail n=1 11 crayfish n=1 12.6 dragonfly n=1 21 leach n=1 15 worm n=1 5.4 trans clam n=1 (all average 11)	6.5 fathead n=1 6.3 shiner n=1 21 mosquitofish (n=2)	6.4 fathead;shiner/8.1 midge=0.8 21 mosquitofish/11 avg invert=1.9	amphipod=0.6 midge, dragonfly=2.9 crayfish=1.6 clam=2.8 leech, worm=2.8? average = 2.1
Lower SDC (up to 25% selenite)	sediment> invertebrate> fish	7.5 corixid (2.3-14) n=4 5.8 crayfish n=1 4.9 snail n=1 7.5 clam (6.1-8.5) n=9 (all average 6.4)	7.8 avg (2.2-14.5) bluegill, carp, fat-head minnow, red shiner, largemouth bass, blk crappie, wht catfish, mixed fish, n=17 17 mosquitofish n=1	7.8 avg fish/7.5 corixid =1.04 17 mosquitofish/6.4 avg=2.6	crayfish=1.6 corixid=2.9 (insect) clam (freshwater) =2.7 average =2.4
IRWD wetlands (up to 39% selenite)	sediment> invertebrate> fish	6.8 zooplankton n=1 11 midge (8-16) n=3 12 corixid (2-24) n=5 5.3 snail n=1 12 crayfish (8-15) n=4 10 dragonfly (12; 7.8) 7.6 clam n=1 (all average 9.2)	13 mixed n=1 19 dead carp n=1 10 mosquitofish n=10	13 mixed/11.5 midge, corixid=1.1 13 mixed/9.2 avg=1.4 10 mosquitofish/9.2 avg =1.1	midge, corixid, dragon= 2.9 crayfish=1.6 copepod=1.6 clam=2.8 snail=2.8 average =2.3
UCI wetlands (up to 100% selenite)	sediment> invertebrate> fish	5.6 dragonfly (3.2; 7.9) 4.2 back-swimmer n=1 (4.9 average)	5.8 mosquitofish n=2	5.8 mosquitofish/4.9=1.2	aquatic insects=2.9
Santa Ana Delhi Channel (up to 11% selenite)	sediment> invertebrate	4.3 clam n=1			clam=2.8

Table 14. Invertebrate and fish Se concentrations for Newport Bay and derivation of bay-specific TTFs for fish. [Means and ranges are shown. The percentage of food items in diets of specific fish species also are given. dw = dry weight; wb = whole-body; n = number of samples.]

species	Upper Bay (µg/g, wb, dw)	Lower Bay (µg/g, wb, dw)	% in diet (Allen and others, 2008)	Upper Bay invertebrate µg/g dw (clapper rail study)[a]	TTF
striped mullet	5.5 (2.4-9.5) n=7		copepod 78% (bivalve 13%)		
California killifish	5.8 (2.6-9.5) n=5	3.9 (1.6-4.6) n=9	bivalve 62% **isopod 3%	6.1 bivalve n=5 2.9 clam n=4 4.4 mussel n=2 4.5 average 8.4 isopod[b]	5.8/4.5= 1.3
shadow goby	5.1 n=1		amphipod 70%	amphipod 4.8 n=1	5.1/4.8 =1.1
arrow goby	4.0 (1.8-8.0) n=4	1.6 n=1	copepod 94%		
cheekspot goby		2.3 (1.4-3.3) n=2	copepod 70%		
anchovy	3.0 (3.0-3.1) n=2		amphipod 99%	amphipod 4.8 n=1	3.0/4.8=0.62
barred sandbass		2.2 (2.2, 2.2) n=2			
spotted sandbass	3.2 (3.1-3.4) n=2		fish 32% bivalve 26% crab 15%	assume fish 3.0 bivalve 6.1 n=5 crab 6.1 n=5	3.2/4.6=0.70
diamond turbot	3.3 (2.4-4.0) n=3	2.7 (1.5-4.0) n=2			
California halibut	4.0 (3.4-4.5) n=4	1.5 (0.9-3.1) n=4	mysid 90% (eating from water column)		
staghorn sculpin	1.6 n=1	2.0 (1.6-2.4) n=3			
black surfperch		1.1 (1.0-1.2) n=3			
shiner perch		1.2 (1.2, 1.2) n=2			
pile surfperch	1.8 (1.7-1.8) n=2	1.7 n=1			
topsmelt	3.4 (1.7-8.0) n=24	2.6 (1.3-4.1) n=26	copepod 57% bivalve 31%	4.5 average of bivalve, clam, mussel	

[a] other data: 6.2 µg/g snail (n=15)

[b] killifish is the only fish that eats isopods (with highest Se in invertebrates, 8.4 µg/g dw)

Table 15. Mean and ranges for bird egg Se concentrations for the San Diego Creek watershed. [dw = dry weight; n = number of samples.]

species	Lower SDC (µg/g, bird egg dw)	IRWD wetlands (µg/g, bird egg, dw)	UCI wetlands (µg/g, bird egg, dw)
American avocet	2.8 (1.9-3.9) n=3*	6.4 (2.0-17.2) n=8	5.1 (3.3-11) n=5
black-necked stilt	6.9 (3.6-8.7) n=11	5.0 (3.0-9.8) n=4	
killdeer	9.5 (9.1-9.9) n=2	4.8 (2.6-7.1) n=2	
American coot	5.2 n=1		2.7 (1.9-4.5) n=9
mallard		6.2 (4.0-7.0) n=4	
pied-billed grebe	5.8 n=1		6.2 (4.0-11) n=4

Table 16. Mean and ranges for bird egg Se concentrations for Upper Newport Bay [dw = dry weight; n = number of samples.]

species	Upper Bay (µg/g, bird egg, dw)
American avocet	5.3 (1.6-10.7) n=12
clapper rail	3.7 (3.1-4.5) n=6
black-necked stilt	5.1 (3.4-8.5) n=3
killdeer	2.6 (2.3-2.9) n=2
tern	4.4 (2.5-8.4) n=18
black skimmer	3.1 (2.1-5.6) n=21

Table 17. Calculated TTFs from laboratory mallard studies; the endpoint is reduced hatchability in eggs (see Ohlendorf, 2003 for complete dataset). [Selenium concentrations in diet and bird eggs used to calculate TTFs also are shown. dw = dry weight; n = number of samples; EC = effect concentration.]

TTF	diet, µg/g dw	bird egg, µg/g dw
1.8	3.6 (EC3)	6.4
2.55	4.9 (EC10)	12.5
2.9	5.7 (EC18)	16.5

Table 18. Modeled Se exposure for the San Diego Creek watershed and Newport Bay. [Two scenarios are shown: scenario A: particulate to invertebrate to average fish to bird; and scenario B: particulate to invertebrate to mosquitofish to bird. The modeled Se criterion is 8.0 µg/g in bird eggs (dw). dw = dry weight; wb = whole-body; n = number of samples; NA = not applicable.]

location	food web	Se in water column (ug/L)	K_d	Se in particulate (µg/g, dw)	TTF for invertebrate	Se in invertebrate (ug/g, dw)	TTF for fish	Se in fish (ug/g wb, dw)	TTF for bird	target Se in bird egg (µg/g dw)
Upper watershed	sediment>insect> average fish>bird	7.0	200	1.4	2.8	4.0	1.1	4.4	1.8	8.0
Upper watershed	sediment>insect> mosquitofish>bird	3.6	200	0.71	2.8	2.0	2.2	4.4	1.8	8.0
Lower SDC	sediment>insect> average fish>bird	4.4	320	1.4	2.8	4.0	1.1	4.4	1.8	8.0
Lower SDC	sediment>insect> mosquitofish>bird	2.2	320	0.71	2.8	2.0	2.2	4.4	1.8	8.0
IRWD wetlands	sediment>insect> average fish>bird	3.5	400	1.4	2.8	4.0	1.1	4.4	1.8	8.0
IRWD wetlands	sediment>insect> mosquitofish>bird	1.8	400	0.71	2.8	2.0	2.2	4.4	1.8	8.0
UCI wetlands	sediment>insect> average fish>bird	1.4	1000	1.4	2.8	4.0	1.1	4.4	1.8	8.0
UCI wetlands	sediment>insect> mosquitofish>bird	0.71	1000	0.71	2.8	2.0	2.2	4.4	1.8	8.0
Near mouth of estuary	sediment>isopod>rail	10.5	200	2.1	2.05	4.4	NA	NA	1.8	8.0
Near mouth of estuary	sediment>clam>rail	3.0	200	0.60	7.4	4.4	NA	NA	1.8	8.0
Near mouth of estuary	sediment>copepod> topsmelt>tern	10.0	200	2.0	2.05	4.0	1.1	4.4	1.8	8.0
Near mouth of estuary	sediment>polychaete> turbot> tern	4.4	200	0.89	4.5	4.0	1.1	4.4	1.8	8.0
Upper Bay	sediment>isopod> scaup or rail	2.1	1000	2.1	2.05	4.4	NA	NA	1.8	8.0
Upper Bay	sediment>clam >scaup or rail	0.60	1000	0.60	7.4	4.4	NA	NA	1.8	8.0
Upper/Lower Bay	sediment>copepod> topsmelt>tern	0.20	10,000	2.0	2.05	4.0	1.1	4.4	1.8	8.0
Upper/Lower Bay	sediment>polychaete> turbot> tern	0.09	10,000	0.89	4.5	4.0	1.1	4.4	1.8	8.0
Lower Bay	sediment>copepod> topsmelt>tern	0.10	20,000	2.0	2.05	4.0	1.1	4.4	1.8	8.0
Lower Bay	sediment>polychaete> turbot> tern	0.04	20,000	0.89	4.5	4.0	1.1	4.4	1.8	8.0

Table 19. Modeled Se exposure for the San Diego Creek watershed and Newport Bay. [The modeled scenario is particulate to invertebrate to bird. The modeled Se criterion is 8.0 µg/g in bird eggs (dw). dw = dry weight; n = number of samples.]

location	food web	Se in water column (ug/L)	K_d	Se in particulate (µg/g, dw)	TTF for invertebrate	Se in invertebrate (ug/g, dw)	TTF for bird	target Se in bird egg (µg/g dw)
Upper watershed	sediment>insect>>bird	8.0	200	1.6	2.8	4.4	1.8	8.0
Lower SDC	sediment>insect>>bird	5.0	320	1.6	2.8	4.4	1.8	8.0
IRWD wetlands	sediment>insect>>bird	4.0	400	1.6	2.8	4.4	1.8	8.0
UCI wetlands	sediment>insect>>bird	1.6	1000	1.6	2.8	4.4	1.8	8.0
Near mouth of estuary	sediment>isopod>rail	10.5	200	2.1	2.05	4.4	1.8	8.0
Near mouth of estuary	sediment>clam>rail	3.0	200	0.60	7.4	4.4	1.8	8.0
Near mouth of estuary	sediment>copepod>bird	10.05	200	2.1	2.05	4.4	1.8	8.0
Near mouth of estuary	sediment>polychaete>bird	4.9	200	0.98	4.5	4.4	1.8	8.0
Upper Bay	sediment>isopod>scaup or rail	2.1	1000	2.1	2.05	4.4	1.8	8.0
Upper Bay	sediment>clam>scaup or rail	0.60	1000	0.60	7.4	4.4	1.8	8.0
Upper/Lower Bay	sediment>copepod>bird	0.21	10,000	2.1	2.05	4.4	1.8	8.0
Upper/Lower Bay	sediment>polychaete>bird	0.098	10,000	0.98	4.5	4.4	1.8	8.0
Lower Bay	sediment>copepod>bird	0.105	20,000	2.1	2.05	4.4	1.8	8.0
Lower Bay	sediment>polychaete>bird	0.049	20,000	0.98	4.5	4.4	1.8	8.0

Table 20. Modeled Se exposure for the San Diego Creek watershed and Newport Bay. [Two scenarios are modeled: scenario A: particulate to invertebrate to average fish; and scenario B: particulate to invertebrate to forage fish to predator fish. The modeled Se guideline is 5.0 µg/g in fish tissue (wb, dw). dw = dry weight; wb = whole-body; n = number of samples; NA = not applicable.]

location	food web	Se in water column (ug/L)	K_d	Se in particulate (µg/g, dw)	TTF for invertebrate	Se in invertebrate (ug/g, dw)	TTF for fish	Se in fish (ug/g wb, dw)	TTF for fish	target Se in fish (µg/g wb, dw)
Upper watershed	sediment>insect> average fish	8.0	200	1.6	2.8	4.5	NA	NA	1.1	5.0
Upper watershed	sediment>iinsect> average fish>LM bass	7.5	200	1.5	2.8	4.1	1.1	4.5	1.1	5.0
Lower SDC	sediment>insect> average fish	5.0	320	1.6	2.8	4.5	NA	NA	1.1	5.0
Lower SDC	sediment>insect> average fish>LM bass	4.7	320	1.5	2.8	4.1	1.1	4.5	1.1	5.0
IRWD wetlands	sediment>insect> average fish	4.0	400	1.6	2.8	4.5	NA	NA	1.1	5.0
IRWD wetlands	sediment>insect> average fish>LM bass	3.8	400	1.5	2.8	4.1	1.1	4.5	1.1	5.0
UCI wetlands	sediment>insect> average fish	1.6	1000	1.6	2.8	4.5	NA	NA	1.1	5.0
UCI wetlands	sediment>insect> average fish>LM bass	1.5	1000	1.5	2.8	4.1	1.1	4.5	1.1	5.0
Near mouth of estuary	sediment>copepod> topsmelt	11	200	2.2	2.05	4.5	NA	NA	1.1	5.0
Near mouth of estuary	sediment>polychaete> turbot	5.0	200	1.0	4.5	4.5	NA	NA	1.1	5.0
Upper Bay	sediment>copepod> topsmelt	2.2	1000	2.2	2.05	4.5	NA	NA	1.1	5.0
Upper Bay	sediment>copepod> topsmelt>halibut	2.0	1000	2.0	2.05	4.1	1.1	4.5	1.1	5.0
Upper Bay	sediment>polychaete> turbot	1.0	1000	1.0	4.5	4.5	NA	NA	1.1	5.0
Upper Bay	sediment>polychaete> turbot>halibut	0.91	1000	0.91	4.5	4.1	1.1	4.5	1.1	5.0
Upper/Lower Bay	sediment>copepod> topsmelt	0.22	10,000	2.2	2.05	4.5	NA	NA	1.1	5.0
Upper/Lower Bay	sediment>copepod> topsmelt>halibut	0.20	10,000	2.0	2.05	4.1	1.1	4.5	1.1	5.0
Upper/Lower Bay	sediment>polychaete> turbot	0.10	10,000	1.0	4.5	4.5	NA	NA	1.1	5.0
Upper/Lower Bay	sediment>polychaete> turbot>halibut	0.09	10,000	0.91	4.5	4.1	1.1	4.5	1.1	5.0
Lower Bay	sediment>copepod>	0.11	20,000	2.2	2.05	4.5	NA	NA	1.1	5.0

location	food web	Se in water column (ug/L)	K_d	Se in particulate (µg/g, dw)	TTF for invertebrate	Se in invertebrate (ug/g, dw)	TTF for fish	Se in fish (ug/g wb, dw)	TTF for fish	target Se in fish (µg/g wb, dw)
	topsmelt									
Lower Bay	sediment>copepod> topsmelt>halibut	0.10	20,000	2.0	2.05	4.1	1.1	4.5	1.1	5.0
Lower Bay	sediment>polychaete> turbot	0.05	20,000	1.0	4.5	4.5	NA	NA	1.1	5.0
Lower Bay	sediment>polychaete> turbot>halibut	0.046	20,000	0.91	4.5	4.1	1.1	4.5	1.1	5.0

Table 21. Generalized modeled Se exposure scenarios for the watershed based on protection for fish. [dw = dry weight.]

Se guideline for fish (µg/g dw)	TTF for fish	Se in invertebrate (µg/g dw)	TTF for aquatic insect	Se in particulate (µg/g dw)	K_d	Se in water column (ug/L)
			Effect of varying K_d			
5	1.1	4.55	2.8	1.62	136 (median)	11.94
5	1.1	4.55	2.8	1.62	168 (mean)	9.66
5	1.1	4.55	2.8	1.62	238 (75th percentile)	6.82
5	1.1	4.55	2.8	1.62	400 (wetland A)	4.06
5	1.1	4.55	2.8	1.62	800 (wetland B)	2.03
5	1.1	4.55	2.8	1.62	791 (UCI wetland mean)	2.05
			Effect of varying fish guideline			
8	1.1	7.27	2.8	2.60	136 (median)	19.10
7	1.1	6.36	2.8	2.27	136 (median)	16.71
6	1.1	5.45	2.8	1.95	136 (median)	14.32
5	1.1	4.55	2.8	1.62	136 (median)	11.94
			Effect of varying fish guideline at a 75th percentile K_d			
8	1.1	7.27	2.8	2.60	238 (75th percentile)	10.91
5	1.1	4.55	2.8	1.62	238 (75th percentile)	6.82

Table 22. Generalized modeled exposure scenarios for the watershed based on protection of birds. [dw = dry weight]

Se guideline for bird egg (µg/g dw)	TTF for bird	Se in fish (µg/g dw)	TTF for fish	Se in invertebrate (µg/g dw)	TTF for aquatic insect	Se in particulate (µg/g dw)	K_d	Se in water column (ug/L)
Effect of varying K_d								
8	1.8	4.44	1.1	4.04	2.8	1.44	136 (median)	10.61
8	1.8	4.44	1.1	4.04	2.8	1.44	168 (mean)	8.59
8	1.8	4.44	1.1	4.04	2.8	1.44	238 (75th percentile)	6.06
8	1.8	4.44	1.1	4.04	2.8	1.44	400 (wetland A)	3.61
8	1.8	4.44	1.1	4.04	2.8	1.44	800 (wetland B)	1.80
8	1.8	4.44	1.1	4.04	2.8	1.44	791 (UCI wetland mean)	1.82
Effect of varying bird egg guideline								
12.5	1.8	6.94	1.1	6.31	2.8	2.25	136 (median)	16.58
12.5	1.8	6.94	1.1	6.31	2.8	2.25	238 (75th percentile)	9.47
Effect of varying TTF for bird								
8	1.6	5.00	1.1	4.55	2.8	1.62	238 (75th percentile)	6.82
8	1.6	5.00	1.1	4.55	2.8	1.62	136 (median)	11.94

Table 23. Model validation for Newport Bay showing predicted and observed fish Se concentrations. [SPM = suspended particulate material; max = maximum; dw = dry weight; n = number of samples.]

food web	Se in particulate (µg/g dw)	TTF for invertebrate	predicted Se in invertebrate (µg/g dw)	TTF for fish	predicted Se in fish (µg/g, wb, dw)	observed Se in fish (mean µg/g, wb, dw)	observed Se range in fish (µg/g, wb, dw)
Upper Bay							
mean SPM>copepod>topsmelt	0.21	2.05	0.43	1.1	0.47	3.4	2.4-9.5 n=7
max SPM>copepod>topsmelt	1.00	2.05	2.05	1.1	2.26		
mean SPM>polychaete>turbot	0.21	4.5	0.94	1.1	1.03	3.3	2.4-4.0 n=3
max SPM> polychaete>turbot	1.00	4.5	4.5	1.1	5.0		
mean SPM>polychaete>killifish	0.21	4.5	0.94	1.1	1.03	5.8	2.6-9.5 n=5
max SPM> polychaete>killifish	1.00	4.5	4.5	1.1	5.0		
mean SPM>clams>turbot	0.21	7.40	1.55	1.1	1.71	3.3	2.4-4.0 n=3
creekSPM>clams>turbot	1.00	7.40	7.40	1.1	8.14		
meanSPM>anchovy>halibut	0.21	1.70	0.36	1.1	0.39	4.0	3.4-4.5 n=4
meanSPM>anchovy>halibut	1.00	1.70	1.70	1.1	1.87		
sediments>mullet	2.00			2.0	4.00	5.5	2.4-9.5 n=7
Lower Bay							
sediments>amphipods>killifish	1.10	0.60	0.66	1.1	0.73	3.9	1.6-4.6 n=9
sediments>amphipods>killifish	2.98	0.60	1.79	1.1	1.97		
sediment>copepod>topsmelt>halibut	1.10	2.05 and 1.1	2.50	1.1	2.75	1.5	0.9-3.1 n=4
sediment>copepod>topsmelt>halibut	2.98	2.05 and 1.1	6.70	1.1	7.40	1.5	
sediment>polychaete>turbot	1.1	4.5	5.0	1.1	5.5	2.7	1.5-4.0 n=2
sediment>polychaete>turbot	2.98	4.5	13.4	1.1	14.7		

Table 24. Model validation for bay showing (1) predicted and observed fish Se concentrations and (2) predicted and observed bird egg Se concentrations. [SPM = suspended particulate material; max = maximum; dw = dry weight; n = number of samples; NA = not available.]

food web	Se in particulate (µg/g dw)	TTF for invertebrate	predicted Se in invertebrate (µg/g dw)	TTF for fish	predicted Se in fish (µg/g, wb, dw)	observed Se in fish (mean µg/g, wb, dw)	TTF for bird	predicted Se in bird egg, (µg/g dw)	observed Se in bird egg (µg/g dw)[a] (skimmer/tern)	Se in bird egg from observed fish (µg/g dw)
Upper Bay										
mean SPM>copepod>topsmelt> skimmer, tern, grebe	0.21	2.05	0.43	1.1	0.47	3.4	1.8	0.85	3.1/4.4	6.1
max SPM	1.00	2.05	2.05	1.1	2.26		1.8	4.07	3.1/4.4	
mean SPM>polychaete>turbot> skimmer, tern, grebe	0.21	4.5	0.94	1.1	1.03	3.3	1.8	1.85	3.1/4.4	5.9
max SPM	1.00	4.5	4.5	1.1	5.0		1.8	9.0	3.1/4.4	
mean SPM>polychaete>killifish> skimmer, tern, grebe	0.21	4.5	0.94	1.1	1.03	5.8	1.8	1.85	3.1/4.4	10.4
max SPM	1.00	4.5	4.5	1.1	5.0		1.8	9.0	3.1/4.4	
mean SPM>clams>turbot> skimmer, tern, grebe	0.21	7.40	1.55	1.1	1.71	3.3	1.8	3.1	3.1/4.4	5.9
max SPM>clams>turbot	1.00	7.40	7.40	1.1	8.14		1.8	14.6	3.1/4.4	
mean SPM>anchovy>halibut> skimmer, ern, grebe	0.21	1.70	0.36	1.1	0.39	4.0	1.8	0.70	3.1/4.4	7.2
max SPM	1.00	1.70	1.70	1.1	1.87		1.8	3.4	3.1/4.4	
mean sediment>mullet> skimmer, tern, grebe	2.00			2.0	4.00	5.5	1.8	7.2	3.1/4.4	9.9
Lower Bay										
sediment>amphipods>killifish> skimmer, tern, grebe	1.10	0.60	0.66	1.1	0.73	3.9	1.8	1.31	3.1/4.4	7.0
max sediment	2.98	0.60	1.79	1.1	1.97		1.8	3.54	3.1/4.4	
sediment>copepod>topsmelt> halibut>pelican, osprey	1.10	2.05 and 1.1	2.50	1.1	2.75	1.5	1.8	4.95	3.1/4.4	2.7
max sediment	2.98	2.05 and 1.1	6.70	1.1	7.40	1.5	1.8	13.32	3.1/4.4	
sediment>polychaete>turbot> skimmer, tern, grebe	1.1	4.5	5.0	1.1	5.5	2.7	1.8	9.9	3.1/4.4	4.9
max sediment	2.98	4.5	13.4	1.1	14.7		1.8	26.5	3.1/4.4	
mean sediment>mullet>skimmer, tern, grebe	2.00			2.0	4.00	5.5	1.8	7.2	3.1/4.4	9.9
sediment	2.00			2.0	4.00	5.5	1.8	7.2	3.1/4.4	

[a] ranges in bird egg Se concentrations (mean, range, and number of samples): skimmer, 3.1 µg/g dw (2.1-5.6) n=21; tern, 4.4 µg/g dw (2.5-8.4) n=18; and grebe, (from watershed) 6.1 µg/g dw (4-11) n=5

Table 25. Model validation for bay showing predicted and observed bird egg Se concentrations. [dw = dry weight; n = number of samples.]

food web	particulate Se (µg/g dw)	TTF for invertebrate	predicted Se in invertebrate (µg/g dw)	TTF for bird	predicted Se in bird egg (µg/g, dw)	observed Se in bird egga (µg/g, dw)	Se in bird egg (range, µg/g, egg dw)	number of samples
Upper Bay								
mean SPM>isopod>avocet	0.21	2.05	0.43	1.80	0.77	5.35	(1.6-10.7)	n=12
creekSPM>isopod>avocet	1.00	2.05	2.05	1.80	3.69	5.35		
mean SPM>isopod>rail	0.21	2.05	0.43	1.80	0.77	3.7	(3.1-4.5)	n=6
creekSPM>isopod>rail	1.00	2.05	2.05	1.80	3.69	3.7		
mean SPM>clams>scaup	0.21	7.40	1.55	1.80	2.80	NA		
creekSPM>clams>scaup	1.00	7.40	7.40	1.80	13.32	NA		
mean SPM>clams>rail	0.21	7.40	1.55	1.80	2.80	3.7	(3.1-4.5)	n=6
creekSPM>clams>rail	1.00	7.40	7.40	1.80	13.32	3.7		
Lower Bay								
sediment>clam>scaup	1.1	7.40	8.14	1.80	14.65	NA		
sediment>clam>scaup	2.98	7.40	22.05	1.80	39.69	NA		
sediment>clam>scaup	2	7.40	14.80	1.80	26.64	NA		
sediment>clam>scaup	2	7.40	14.80	1.80	26.64	NA		

[a] additional bird egg Se concentrations (mean, range, and number of samples): stilt, 5.1 µg/g dw (3.4-8.5) (n=3); and killdeer, 2.6 µg/g dw (2.3-2.9) (n=2)

Table 26. Model validation for watershed showing (1) predicted and observed invertebrate Se concentrations and (2) predicted and observed bird egg Se concentrations. [dw = dry weight; n = number of samples]

location	food web	invertebrate	Se in particulate (µg/g dw)	TTF for invertebrate	predicted Se in invertebrate (µg/g dw)	observed in invertebrate (average)	TTF for bird	predicted Se in bird egg (µg/g, dw)	observed Se in bird egg (µg/g, dw)	species and number of samples
Lower SDC	sediment>invertebrate> avocet	corixid, crayfish, snail, clam	1.2 2.8	2.8 2.8	3.4 7.8	6.2	1.8 1.8	6.2 14.0	2.8 (1.9-3.9)	avocet (3)
Lower SDC	sediment>invertebrate> stilt	corixid, crayfish, snail, clam		2.8			1.8		6.9 (3.6-8.7)	stilt (11)
Lower SDC	sediment>invertebrate> killdeer	corixid, crayfish, snail, clam		2.8			1.8		9.5 (9.1-9.9)	killdeer (2)
Lower SDC	sediment>invertebrate> grebe	corixid, crayfish, snail, clam		2.8			1.8		5.8	pied-billed grebe (1)
Lower SDC	sediment>invertebrate> coot	corixid, crayfish, snail, clam		2.8			1.8		5.2	coot (1)
IRWD wetlands	sediment>invertebrate> avocet	midge, corixid, dragonfly	3.7 5.3	2.8	10.4 14.8	10.9	1.8	18.7 26.6	6.4 (2-17.2)	avocet (8)
IRWD wetlands	sediment> invertebrate> stilt	zooplankton, midge, corixid, snail, crayfish, dragonfly, clam		2.8			1.8		5 (3-9.8)	stilt (4)
IRWD wetlands	sediment> invertebrate> mallard	zooplankton, midge, corixid, snail, crayfish, dragonfly, clam		2.8			1.8		6.2 (4-7)	mallard (4)
IRWD wetlands	sediment> invertebrate> killdeer	zooplankton, midge, corixid, snail, crayfish, dragonfly, clam		2.8			1.8		4.8 (2.6-7.1)	killdeer (2)
UCI wetlands	sediment> invertebrate> coot	dragonfly	2.2	2.8	6.2	5.6	1.8	11.2	2.7 (1.9-4.5)	coot (9)
UCI wetlands	sediment> invertebrate> avocet	dragonfly		2.8			1.8		5.1 (3.3-11)	avocet (5)
UCI wetlands	sediment> invertebrate> grebe	dragonfly		2.8			1.8		6.2 (4-11)	pied-billed grebe (4)

Table 27. Model validation for watershed showing (1) predicted and observed fish Se concentrations and (2) predicted and observed bird egg Se concentrations. [dw = dry weight; n = number of samples.]

location	food web	fish species	particulate Se (µg/g dw)	TTF for invertebrate	predicted Se in inverte-brate (µg/g dw)	TTF for fish	predicted Se in fish (µg/g dw)	average observed in fish[a]	TTF for bird	predicted Se in bird egg (µg/g, dw)	observed Se in bird egg (µg/g, dw)	species and number of samples
Lower San Diego Creek	sediment> invert>fish>bird	average fish	1.2 2.8	2.8	3.4 7.8	1.1 1.1	3.7 8.6	8.4	1.8	15.1	5.8	pied-billed grebe (1)
IRWD wetlands	sediment> invert>fish>bird	average fish	3.7 5.3	2.8	10.4 14.8	1.1 1.1	11.4 16.3	14	1.8	25.2		
UCI wetlands	sediment> invert> grebe	average fish	2.2	2.8	6.2	1.1	6.8	5.8	1.8	10.4	6.2 (4-11)	pied-billed grebe (4)

[a] mosquitofish for marsh drains, lower San Diego Creek, and Lower Peters Canyon Wash were 12.5, 17 and 21 µg/g dw, respectively; thus, transfer for mosquitofish at these sites are underestimated by a TTF of 1.1 (see table 11 for range of TTFs for mosquitofish)

Table 28. Model validation for watershed showing predicted and observed bird egg Se concentrations. [dw = dry weight; n = number of samples.]

location	food web	Se in fish (μg/g, wb, dw)	fish species	TTF for bird	predicted Se in bird egg (μg/g, dw)	observed Se in bird egg (μg/g, dw)	species and number of bird egg samples
Upper SDC and PCW	sediment>invert>fish>bird	5.8	mixed fish	1.8	10.4		
Marsh drains	sediment>invert>fish>bird	12.5	mosquitofish	1.8	22.5		
Lower SDC	sediment>invert>fish>bird	7.8	bluegill, common carp, fathead minnow, red shiner, largemouth bass, black crappie, white catfish, mixed fish	1.8	14.0	5.8	pied-billed grebe (1)
Lower SDC	sediment>invert>fish>bird	17	mosquitofish	1.8	30.6		
Lower PCW	sediment>invert>fish>bird	6.4	fathead minnow, red shiner	1.8	11.5		
Lower PCW	sediment>invert>fish>bird	21	mosquitofish (12.1; 29.9)	1.8	37.8		
IRWD wetlands	sediment>invert>fish>bird	19.3	dead carp (filet)	1.8	34.7		
IRWD wetlands	sediment>invert>fish>bird	13	mixed fish	1.8	23.4		
IRWD wetlands	sediment>invert>fish>bird	10.1	mosquitofish (2.3; 15.3)	1.8	18.2		
UCI wetlands	sediment>invert>fish>bird	5.8	mosquitofish	1.8	10.4	6.2 (4.0-11)	pied-billed grebe (4)

Figures
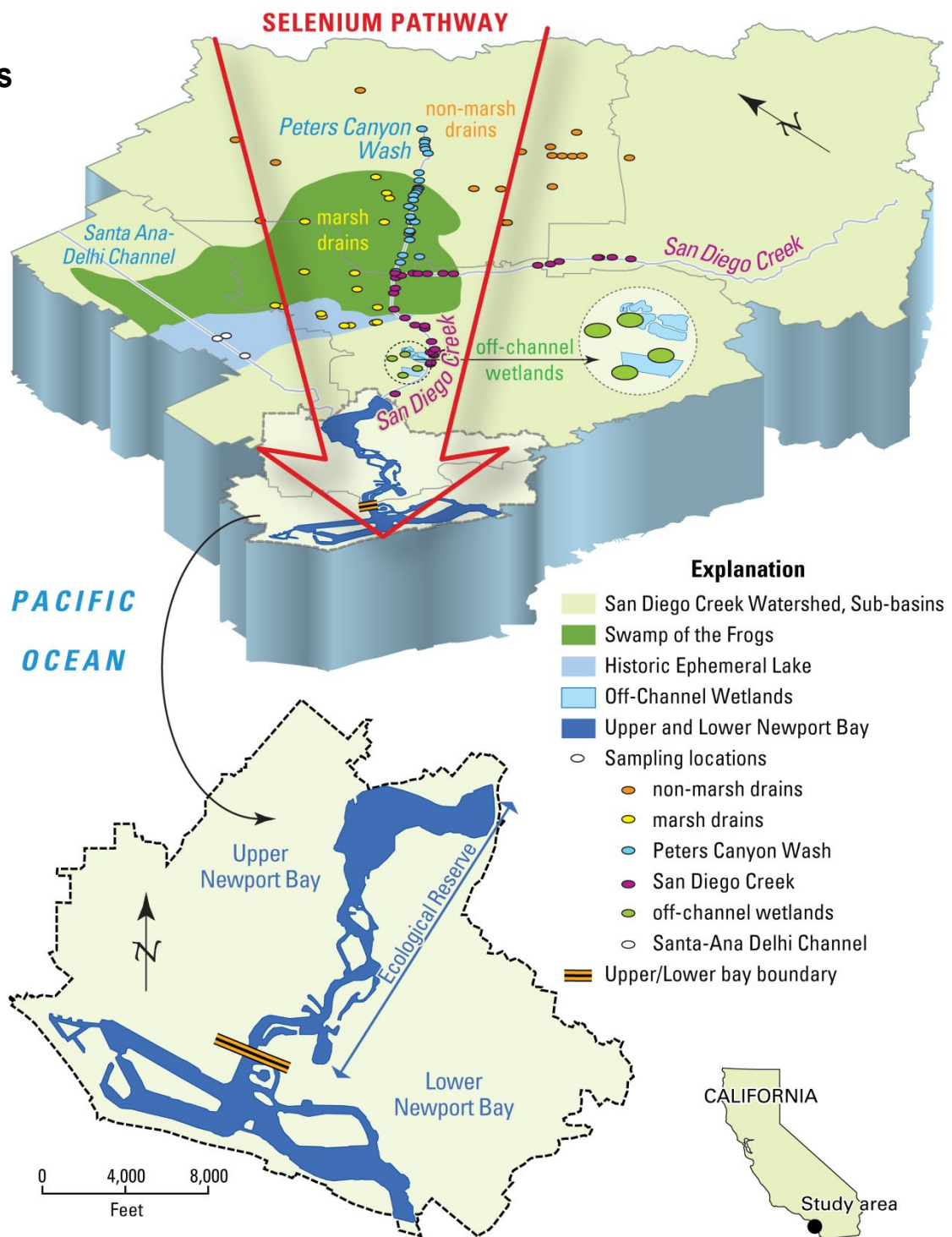
Figure 1. Schematic block diagram of the San Diego Creek watershed and Newport Bay highlighting assessment areas and Se pathway. Map enlargement shows Upper and Lower Newport Bay.

San Diego Creek Selenium Model

source loads	÷	source volumes

||

concentration in drains, creeks, wetlands, and at mouth of estuary: dissolved species (selenate; selenite; organo-Se)

$\downarrow K_d$

concentration in algae, suspended material, sediment:
particulate species (Se(0), adsorbed selenite; org-Se)

$\downarrow$ **TTF$_{invertebrate}$**

concentration in invertebrates
zooplankton, aquatic insects, crayfish, clam, snail, worm, leech

TTF$_{fish}$

$\downarrow$ **TTF$_{fish}$** $\downarrow$ **TTF$_{bird}$**   **TTF$_{bird}$**

concentration in fish
minnow, bluegill, carp, shiner, bass, crappie, catfish, mosquitofish

TTF$_{bird}$ →

concentration in birds
avocet, stilt, rail, killdeer, coot, mallard, grebe

Figure 2. Conceptual model for the San Diego Creek watershed illustrating linked factors that determine the effects of Se on ecosystems.

Upper Newport Bay Selenium Model

watershed source loads	÷	watershed source volumes

||

concentration in upper bay:
dissolved species (selenate; selenite; organo-Se)

$\downarrow K_d$

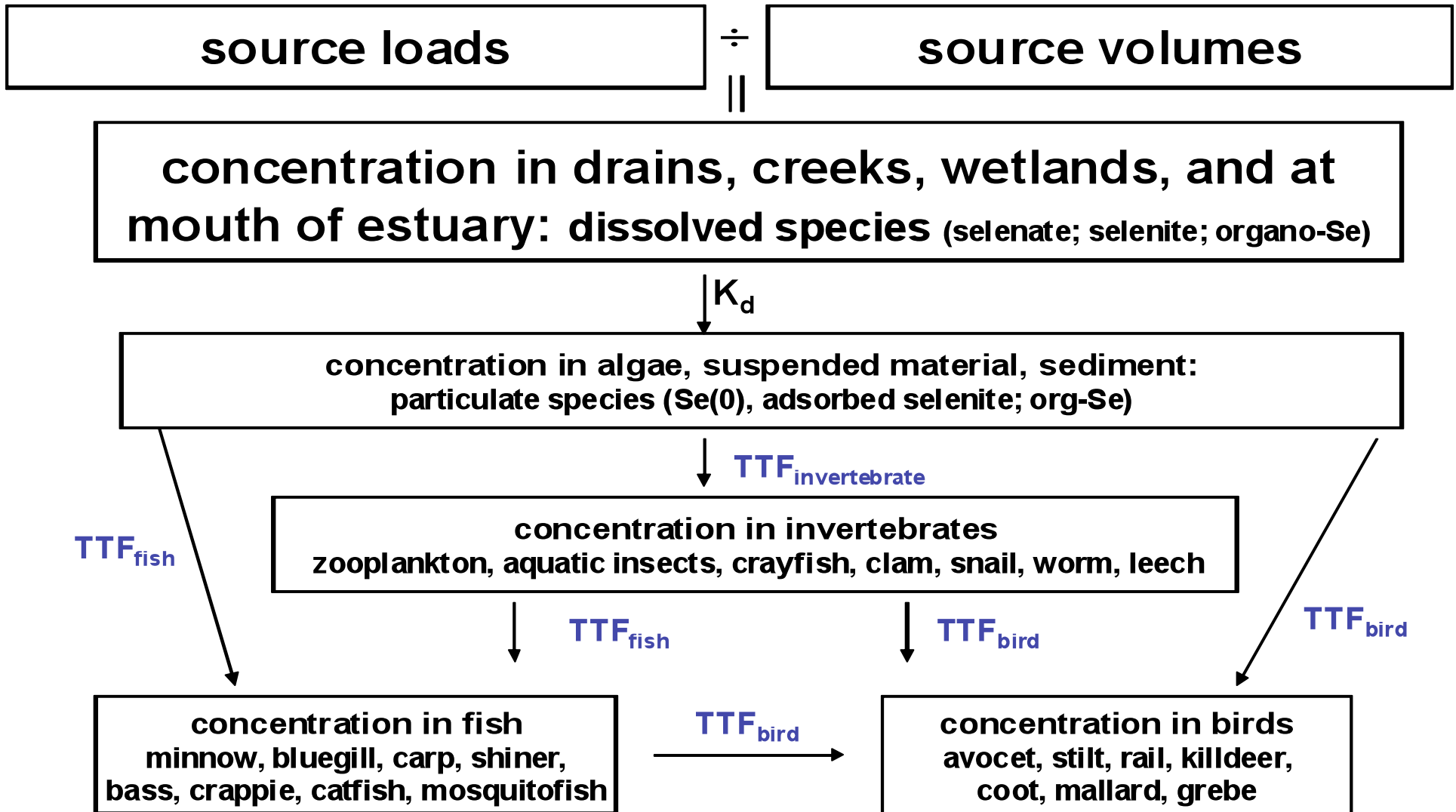**concentration in algae, suspended material, sediment:**
particulate species (Se(0), adsorbed selenite; org-Se)

$\downarrow$ **TTF$_{invertebrate}$**

TTF$_{fish}$

concentration in invertebrates
amphipod, isopod, crayfish, clam, mussel, crab, snail

$\downarrow$ **TTF$_{fish}$** $\downarrow$ **TTF$_{bird}$**   **TTF$_{bird}$**

concentration in fish
mullet, killifish, goby, anchovy, sandbass, turbot, halibut, sculpin, perch, topsmelt

TTF$_{bird}$ →

concentration in birds
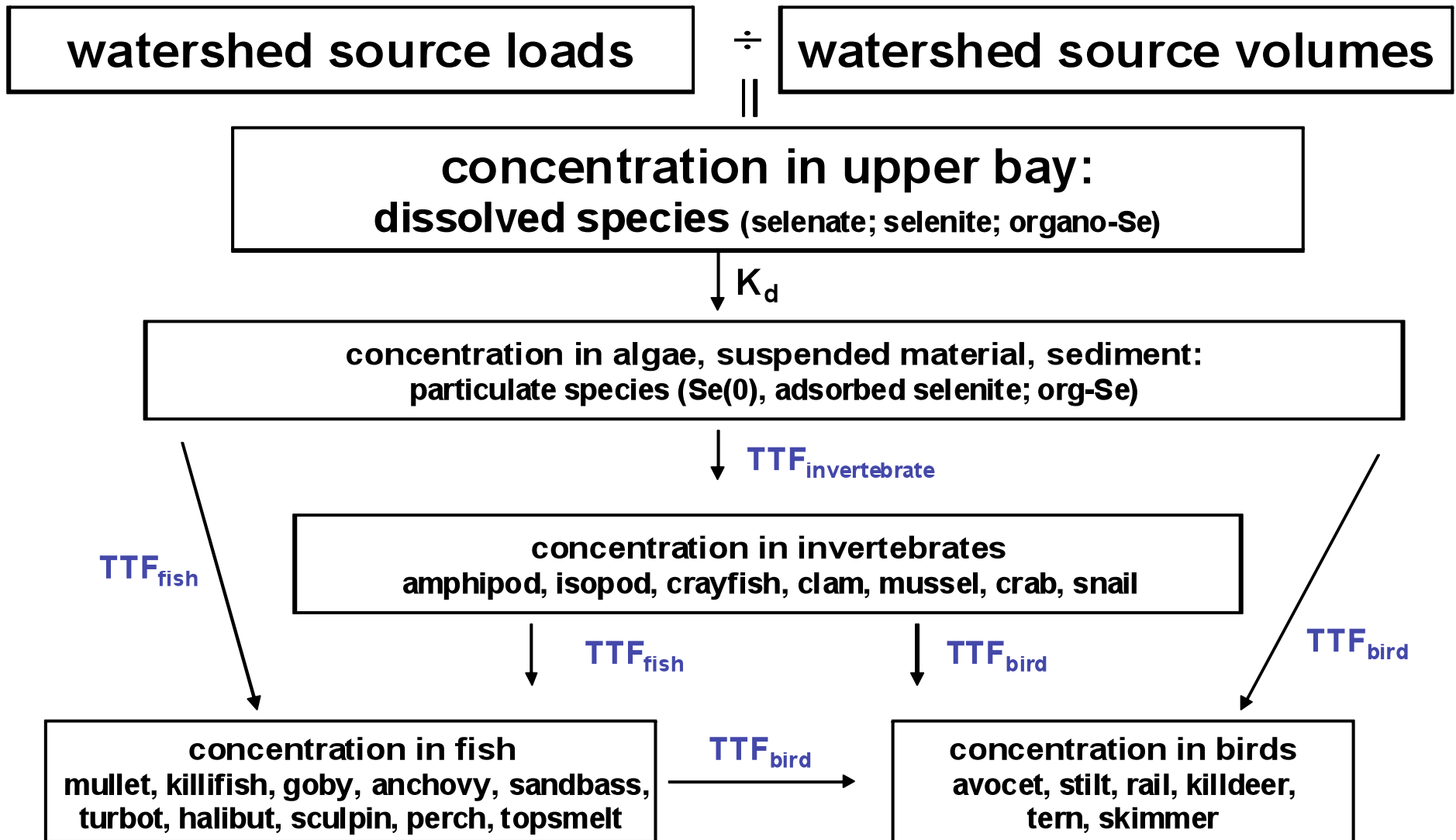**avocet, stilt, rail, killdeer, tern, skimmer**

Figure 3. Conceptual model for the Upper Newport Bay illustrating linked factors that determine the effects of Se on ecosystems.
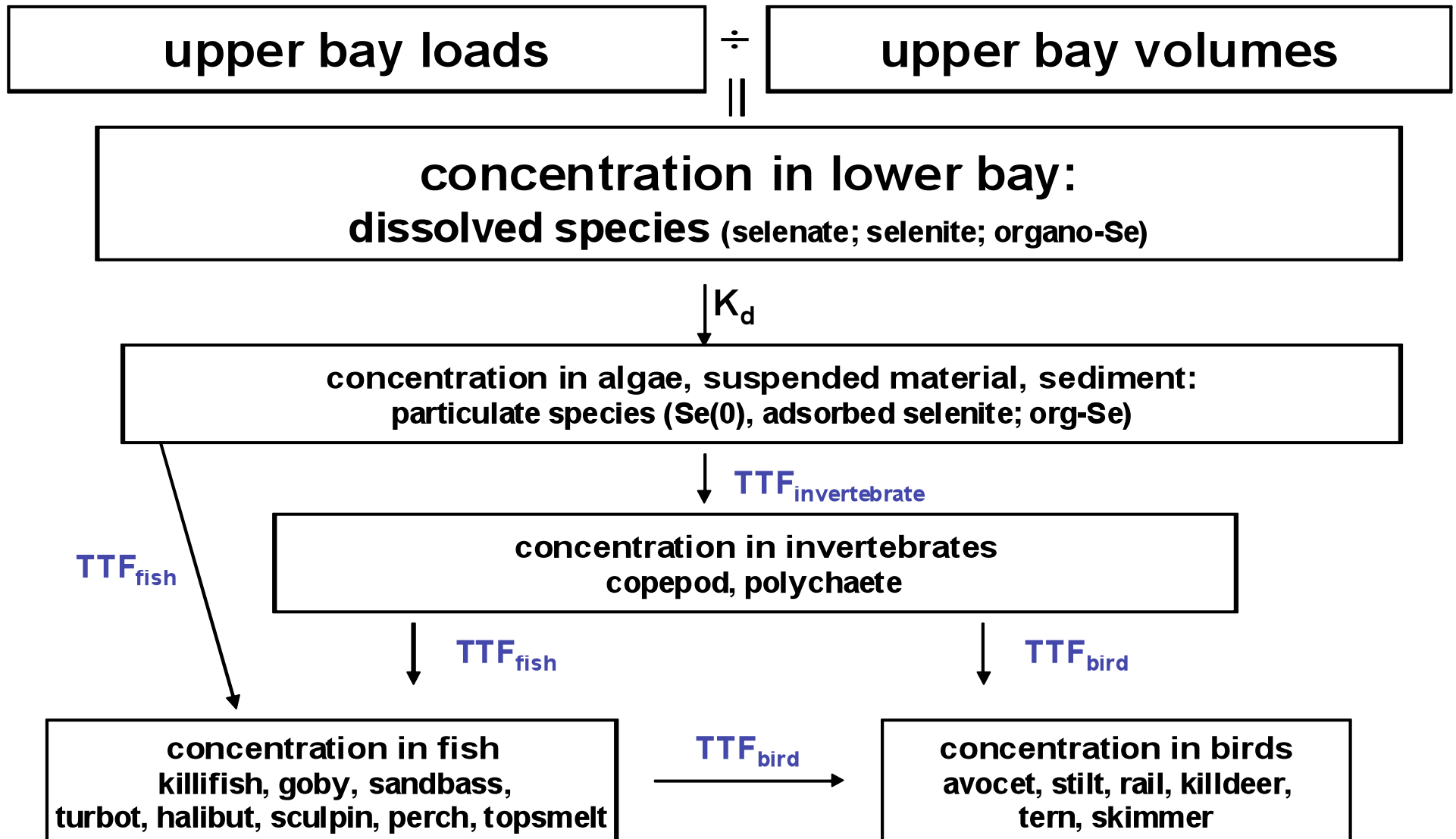
Lower Newport Bay Selenium Model

upper bay loads	$\div$	upper bay volumes

$\parallel$

concentration in lower bay:
dissolved species (selenate; selenite; organo-Se)

$\downarrow K_d$

concentration in algae, suspended material, sediment:
particulate species (Se(0), adsorbed selenite; org-Se)

$\downarrow$ **TTF$_{invertebrate}$**

TTF$_{fish}$

concentration in invertebrates
copepod, polychaete

$\downarrow$ **TTF$_{fish}$** $\downarrow$ **TTF$_{bird}$**

concentration in fish
killifish, goby, sandbass,
turbot, halibut, sculpin, perch, topsmelt

TTF$_{bird}$ $\longrightarrow$

concentration in birds
avocet, stilt, rail, killdeer,
tern, skimmer

Figure 4. Conceptual model for the Lower Newport Bay illustrating linked factors that determine the effects of Se on ecosystems.
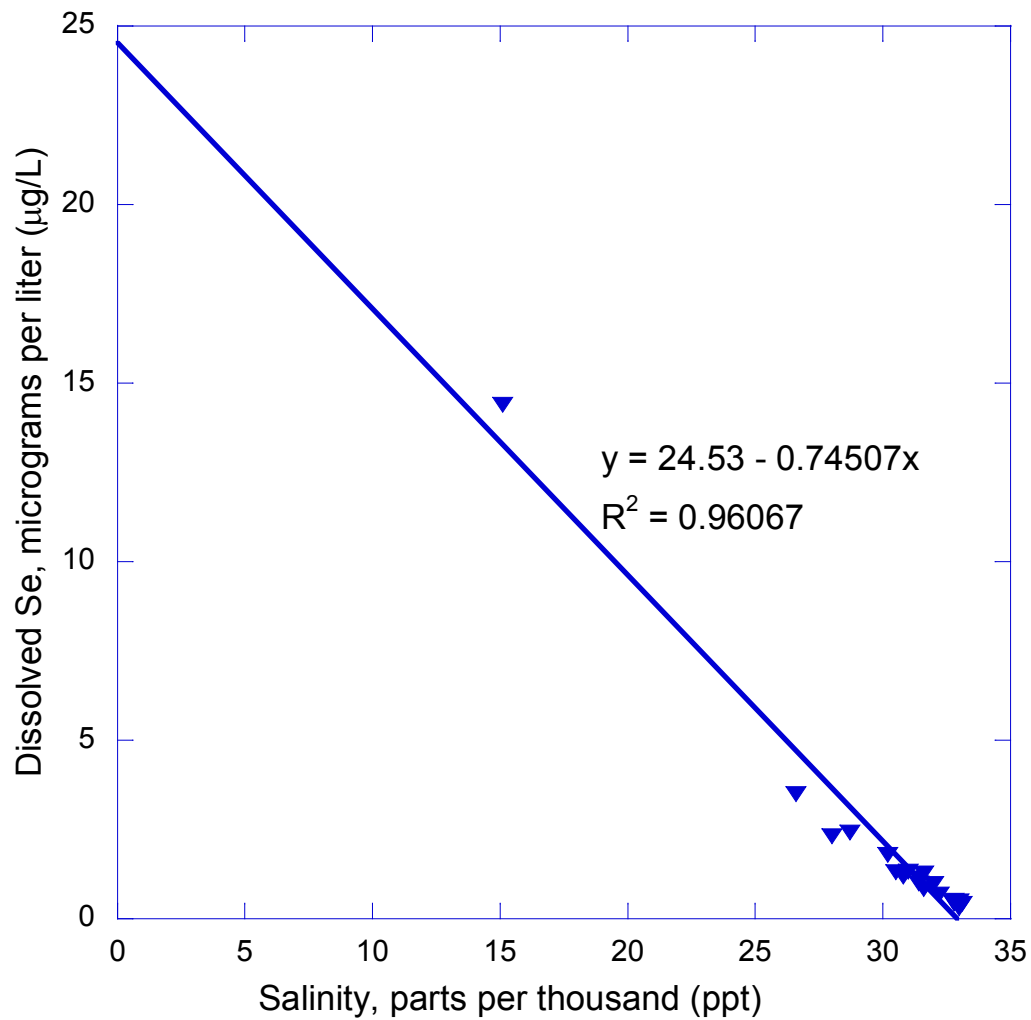
Figure 5. Extrapolation of dissolved Se to 0 ppt. Data from transect of the Upper Newport Bay from near the mouth of San Diego Creek into the upper bay (CH2M Hill, 2008a).