Forecasting Selenium Discharges to the San Francisco Bay-Delta Estuary: Ecological Effects of A Proposed San Luis Drain Extension

Open-File Report 00-416

U.S. Department of the Interior
U.S. Geological Survey

FORECASTING SELENIUM DISCHARGES TO THE SAN FRANCISCO BAY-DELTA ESTUARY: ECOLOGICAL EFFECTS OF A PROPOSED SAN LUIS DRAIN EXTENSION

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U.S. GEOLOGICAL SURVEY

Open-File Report 00-416

Water Resources Division
National Research Program

This project has been funded in part by the United States Environmental Protection Agency Interagency Agreement DW-14-95534701-4 (Region 9, Water Division) and Joint Funding Agreements with Contra Costa County and Contra Costa Water District. The contents of this document do not necessarily reflect the views and policies of the U.S. Environmental Protection Agency, Contra Costa County, or Contra Costa Water District.

Menlo Park, California
2000

U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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- in years with different climate regimes;
- in different seasons; and
- for alternative speciation and biogeochemical behavior patterns.

The scenarios considered are:

- a SLD extension discharge of 18,700 lbs per six months (full capacity, 62.5 μg Se/L);
- a SJR discharge of a targeted load of 3,590 lbs per six months for a wet year (1.2 μg Se/L) and 3,400 lbs per six months for a dry year (2.5 μg Se/L).

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- concentrations in the North Bay near the site of input (i.e., head of estuary) with instantaneous mixing; and
- the low flow season of a dry year.

Conditions prior to refinery cleanup are given for comparison.

CONVERSION FACTORS

By weight: microgram per gram is equivalent to parts per million (ppm)
1 microgram (μg/g) = 10^{-6} gram (g)
For concentration of dissolved solids less than approximately 7,000 mg/L:
Milligram per liter (mg/L) is equivalent to parts per million
Microgram per liter (μg/L) is equivalent to parts per billion (ppb)
1,000 microgram per liter (μg/L) = 1 milligram per liter (mg/L)
See also Table 4 (in text) which is duplicated below.

Selenium (Se)	**Salt or Total Dissolved Solids (TDS)**
1 ppb Se =1 μg Se/L	1 ppm TDS = 1 mg salt/L
1 gallon = 3.785 Liters	1 gallon = 3.785 Liters
1 acre-foot = 325,900 gallons = 1,233,532 liters	1 acre-foot = 325,900 gallons = 1,233,532 liters
1,233,532 μgrams Se/acre-foot at 1 ppb Se	
1.23 grams Se/ acre-foot at 1 ppb Se	1,234 grams salt/acre-foot at 1 ppm salt
454 grams = 1 lb	
0.00272 lbs Se/acre-foot at 1 ppb Se	2.72 lbs salt/acre-foot at 1 ppm salt
[1 ppb Se = 0.00272 lbs Se/acre-foot]	[1 ppm salt= 2.72 lbs salt/acre-foot]
	2000 lbs = 1 ton
	1 ppm salt = 0.00136 tons salt/acre-foot
VOLUME	
1 cubic foot per second (cfs) = 1.98 acre-feet/day	

For those who prefer to use the International System of Units (SI), the conversion factors for terms used in this report are listed below.

Multiply	By	To obtain
Acre	4,047	square meter (m^2)
Acre	0.4047	hectare (ha)
acre-foot	1,233	cubic meter (m^3)
cubic foot per second (cfs)	0.02832	cubic meters per second (m^3/s)

ABBREVIATIONS

AF	Acre-foot
AE	Assimilation Efficiency
BAF	Bioaccumulation Factor
BSAF	Biota to Sediment Accumulation Factor
Bay-Delta	San Francisco Bay-Delta Estuary
CALFED	A cooperative, interagency effort of fifteen federal and state agencies with management and regulatory responsibilities for the Bay-Delta
CCtF	Clifton Court Forebay
CCVRWQCB	California Central Valley Regional Water Quality Control Board
CDFG	California Department of Fish and Game
CDWR	California Department of Water Resources
CSFBRWQCB	California San Francisco Bay Regional Water Quality Control Board
CSWRCB	California State Water Resources Control Board
CVP	Central Valley Project
dw	dry weight
DynBaM	Dynamic Multi-path Bioaccumulation Model
FR	Feeding Rate
GBCP	Grassland Bypass Channel Project
K_d	Distribution (partitioning) coefficient
kst	kesterson unit (equals 17,400 lbs Se)
MAF	Million Acre-Feet
NMFS	National Marine Fisheries Service
psu	practical-salinity unit
Sac R	Sacramento River
SJR	San Joaquin River
SJV	San Joaquin Valley
SJVDP	San Joaquin Valley Drainage Program
SLD	San Luis Drain
SLU	San Luis Unit
SWP	State Water Project
TMDL	Total Maximum Daily Load
TMML	Total Maximum Monthly Load
USBR	United States Bureau of Reclamation
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WWD	Westlands Water District
WY	Water Year (A water year begins on October 1st)

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ABSTRACT

During the next few years, federal and state agencies may be required to evaluate proposals and discharge permits that could significantly change selenium (Se) inputs to the San Francisco Bay-Delta Estuary (Bay-Delta), particularly in the North Bay (i.e., Suisun Bay and San Pablo Bay). These decisions may include discharge requirements for an extension of the San Luis Drain (SLD) to the estuary to convey subsurface agricultural drainage from the western San Joaquin Valley (SJV), a renewal of an agreement to allow the existing portion of the SLD to convey subsurface agricultural drainage to a tributary of the San Joaquin River (SJR) (coincident with changes in flow patterns of the lower SJR), and refinements to promulgated Se criteria for the protection of aquatic life for the estuary.

Understanding the biotransfer of Se is essential to evaluating the fate and impact of proposed changes in Se discharges to the Bay-Delta. However, past monitoring programs have not addressed the specific protocols necessary for an element that bioaccumulates. Confusion about Se threats in the past have stemmed from failure to consider the full complexity of the processes that result in Se toxicity. Past studies show that predators are more at risk from Se contamination than their prey, making it difficult to use traditional methods to predict risk from environmental concentrations alone. In this report, we employ a novel procedure to model the fate of Se under different, potentially realistic load scenarios from the SJV. For each potential load, we progressively forecast the resulting environmental concentrations, speciation, transformation to particulate form, bioaccumulation by invertebrates, trophic transfer to predators, and effects in those predators. Enough is known to establish a first order understanding of effects should Se be discharged directly into the North Bay via a conveyance such as the SLD.

Our approach uses 1) existing knowledge concerning the biogeochemical reactions of Se (e.g.,

speciation, partitioning between dissolved and particulate forms, and bivalve assimilation efficiency) and 2) site-specific data mainly from 1986 to 1996 on clams and bottom-feeding fish and birds. Forecasts of Se loading from oil refineries and agricultural drainage from the SJV enable the calculation of a composite freshwater endmember Se concentration at the head of the estuary and at Carquinez Strait as a foundation for modeling. Our analysis of effects also takes into account the mode of conveyance for agricultural drainage (i.e., the SLD or SJR). The effects of variable flows on a seasonal or monthly basis from the Sacramento River and SJR are also considered.

The results of our forecasts for external SJV watershed sources of Se mirror predictions made since 1955 of a worsening salt (and by inference, Se) buildup exacerbated by the arid climate and irrigation for agricultural use. We show that the reservoir of Se in the SJV is sufficient to provide loading at an annual rate of approximately 42,500 pounds (lbs) of Se to a Bay-Delta disposal point for 63 to 304 years at the lower range of our projections, even if influx of Se from the California Coast Ranges could be curtailed. Disposal of wastewaters on an annual basis outside of the SJV may slow the degradation of valley resources, but drainage alone cannot alleviate the salt and Se buildup in the SJV, at least within a century.

Our forecasts show the different proportions of Se loading to the Bay-Delta. Oil refinery loads from 1986 to 1992 ranged from 11 to 15 lbs Se per day; with treatment and cleanup, loads decreased to 3 lbs Se per day in 1999. In contrast, SJV agricultural drainage loads could range from of 45 to 117 lbs Se per day across a set of reasonable conditions. Components of this valley-wide load include five source subareas (i.e., Grassland, Westlands, Tulare, Kern, and Northern) based on water and drainage management. Loads vary per subarea mainly because of proximity of the subarea to geologic sources and irrigation history. Loads from the Sacramento River, depending on flow conditions, range from 0.8 to 10 lbs Se per day.

A consistent picture of ecological risk emerges for the Bay-Delta based on concurrent lines of evidence. The threat to the estuary is greatest during low flows and dry years. Where Se undergoes reactions typical of low flow or longer residence time, highly problematic bioaccumulation in prey (food) is forecast to result. The Bay-Delta predators—surf scoter, greater and lesser scaup, and white sturgeon—appear to be most at risk because they feed on filter-feeding bivalves. Recent findings add Sacramento splittail to that list. During the low flow season of dry years, the lower range of proposed protective guidelines for waterborne, particulate, dietary, and predator tissue Se is exceeded under the most likely forecast of Se inputs from a proposed SLD extension. Also under low flow conditions, the upper range of guidelines (i.e., high certainty of adverse effects) is exceeded in all instances except at the lowest load considered. High flows afford some protection in the forecast SJR scenarios under certain conditions. However, meeting a combined goal of releasing a specific load during maximum flows and keeping Se concentrations below a certain objective to protect against bioaccumulation may not always be attainable. Management of the SJR on a constant concentration basis could also create problematic bioaccumulation during a wet year, especially during the low flow season, because high flows translate to high loads that are not always offset by seasonal inflows.

Prior to refinery cleanup, Se contamination was sufficient to threaten reproduction in key species within the Bay-Delta ecosystems and human health advisories were posted based on Se concentrations in livers of diving ducks. During this time, Se concentrations in the Bay-Delta were well below the most stringent water quality criteria. Enhanced biogeochemical transformations to bioavailable particulate Se and efficient uptake by bivalves and then predators characterized the system. If these biogeochemical conditions continue to prevail, the forecasts suggest the risk of adverse effects will be difficult to eliminate under an out-of-valley resolution to the Se problem.

The forecasts for Se loading present a new tool to evaluate ecological effects based upon the major processes leading from loads through consumer organisms to predators. It is a feasible approach for site-specific analysis and could provide a framework for developing new protective criteria. We conclude that credible protective criteria should be based on 1) contaminant concentrations in sources, such as particulate material, that most influence bioavailability and 2) concentrations in media and organisms relevant to vulnerable food webs. Existing criteria for water, particulate material, and tissue of prey and predators should be used in combination to evaluate risk or hazard. Bivalves appear to be the most sensitive indicator of Se contamination in the Bay-Delta.

INTRODUCTION

The sources and biogeochemistry of Se combine to make contamination with this element an ecological issue of widespread concern [Trelease and Beath, 1949; National Research Council, 1976; 1989, U.S. Environmental Protection Agency (USEPA), 1980; 1987; 1992; 1998; Wilber, 1983; also see compilations in Frankenberger and Benson, 1994; Lemly, 1995; Frankenberger and Engberg, 1998; Skorupa, 1998a; Seiler et al., 1999; Hamilton, 1999; Eisler, 2000; Hamilton, 2000a]. Selenium is especially enriched in organic-rich shales that are source rocks for oil, coal, and phosphate ores (Figure 1) (Cumbie and Van Horn, 1978; Presser, 1999; Piper et al., 2000). Release of Se to aquatic systems is a result of weathering and anthropogenic activities such as refining, power production, and mining. Selenium is also enriched in the soils and runoff derived from these source sedimentary shales in many semi-arid regions exploited for irrigated agriculture, such as in the SJV, California (Presser, 1994a; b; Seiler et al., 1999). Salinization of some of these soils is accompanied by Se contamination that increases the complexity of problems associated with continued exploitation of such lands (SJV Drainage Program, 1990a; Dinar and Zilberman, 1991). Irrigation, leaching, and generation of subsurface drainage leads to surface and ground waters being contaminated (Presser and Ohlendorf, 1987). Treatment technologies for Se have utilized both chemical and biological processes to remove Se from the water column, but with little operational success or cost-effectiveness (SJV Drainage Program, 1990a; Hanna et al., 1990; SJV Drainage Implementation Program, 1998; 1999a). Use of large-scale biological treatment technologies (e.g. wetlands or evaporation ponds) has generated serious ecological problems and hazardous Se wastes for disposal (Presser and Piper, 1998; Skorupa, 1998a; Hamilton, 2000b). Selenium removal is further hampered by the failure of traditional chemical methods to reduce Se to levels acceptable for remediation and, in arid regions, by the problem of disposal of associated salts (SJV Drainage Program, 1990a). Remediation has not been established other than that dependent on dilution in a larger body of water (SJV Drainage Implementation Program, 1998; U.S. Department of the Interior's National Irrigation Water Quality Program, 2000). Management plans for the western SJV that include drainage storage and reduction through source control have been developed, but systematic and comprehensive implementation has not taken place (SJV Drainage Program, 1990a; SJVDP, 1991; SJV Drainage Implementation Program, 1998; Environmental Defense Fund, 1994).

The biogeochemical cycling of Se and its role as an essential nutrient lead to the dominance of biological reactions over thermodynamic reactions in aquatic systems (Shrift, 1964; Stadtman, 1974; National Research Council, 1976; Measures and Burton, 1978; Cutter and Bruland, 1984; Lemly, 1985; Presser and Ohlendorf, 1987; Oremland et al., 1989; Luoma et al., 1992; Maier and Knight, 1994; Presser, 1994a; Lemly, 1997b; Wang et al., 1996; Luoma and Fisher, 1997; Dowdle and Oremland, 1999; Reinfelder et al., 1998). The fate and adverse ecological effects of Se discharges are determined by a sequence of linked processes that connect loads, concentrations, speciation, bioavailability, trophic transfer, and effects on predators (Luoma et al., 1992; Luoma, 1996; Wang et al., 1996; Reinfelder et al., 1997; 1998; Luoma and Fisher, 1997) (Figure 2). Pathway bioaccumulation models allow consideration of 1) biotransfer from different types of suspended/particulate matter (e.g., phytoplankton, seston, and benthos); 2) biotransformation to different speciation regimes (selenate, selenite, organo-Se, elemental Se); 3) bioaccumulation via the lower trophic food web; and 4) uptake of food by predator species. Because Se concentrations can be magnified at each step of food web transfer (e.g., USEPA, 1980; Saiki, 1986; Maier and Knight, 1994), upper trophic level species are probably the species most vulnerable to adverse effects from Se contamination. Aquatic species potentially at risk from Se contamination (Figure 1) include charismatic birds (e.g., ducks, shorebirds, and grebes) and fish (e.g., sturgeon, carp, trout, and sunfish) (White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991; Luoma et al., 1992; Lemly, 1993a; 1998a; b; Skorupa, 1998a). Herps (frogs and snakes) also may be at risk from Se [Skorupa, 1998b; U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS), 1998 and amended, 2000), as may Sacramento splittail (Stewart, et al., in preparation).

Analysis of one of the above sets of processes, in isolation, is inadequate to characterize Se problems (Luoma and Fisher, 1997). If correlations made among factors or processes skip links, then serious uncertainties will result. Failure to consider the full sequence of interacting processes is a major cause of controversy surrounding many interpretations of Se effects on the environment (e.g., O'Toole and Raisbeck, 1998; Hamilton and Lemly, 1999; Chapman, 1999; Lemly, 1999a; Skorupa, 1998a; 1999). In view of advances in the understanding of Se environmental chemistry, the USEPA has recently called for a re-definition of the Se criteria for the protection of aquatic life (USEPA, 1998; Renner, 1998).

Selenium contamination of aquatic ecosystems is of special concern in large areas of California, and other semi-arid regions of western North America (Presser, 1994a; b; Seiler et al., 1999). Selenium issues are of particular concern in the SJR basin (Figure 3) and in the Bay-Delta (Figure 4). Here, Se issues are intricately interwoven with issues of water management, urbanization, irrigated agriculture, and protection of fish and wildlife resources [Conomos, 1979; Conomos et al., 1985; Cloern and Nichols, 1985; Nichols et al., 1986; California State Water Resources Control Board (CSWRCB), 1994; 1999a; USFWS, 1995; Hollibaugh, 1996; Presser and Piper, 1998; CALFED, 1998a; b; 1999a; b; c; d; Thompson et al., 2000]. The SJV has also suffered major losses of crucial habitat for migratory birds (Gilmer at al., 1982; Vencil, 1986).

The goal of this paper is to introduce a comprehensive approach to forecast the ecological effects of Se under an array of scenarios that could result from different resolutions of water and waste management issues. We concentrate on analysis of Se inputs based on engineering solutions that would convey Se-laden salts from the western SJV to the Bay-Delta via a proposed extension of the San Luis Drain (SLD) (Barcellos, 1986; Wanger, 1994; CSWRCB, 1996b; c; 1999a; d; Stevens and Bensing, 1994; Contra Costa County, 1997; San Joaquin River Exchange Contractors Water Authority, 1999; Trinity County, 1999; U.S. House of Representatives, 1999; Hug, 2000). We also consider using the SJR as a conveyance facility (i.e., the SJR as a *de facto* drain) because it is the only natural outlet from the SJV. We present a history of the discussions surrounding the construction of the drain and use of the SJR to convey Se outside the SJV. We forecast loads, concentrations, fate, and effects of Se on animals in the estuarine food web that could result from projected Se discharges.

Our approach involves using existing knowledge, that includes empirical observations from the Bay-Delta and models, to convert proposed mass emissions to concentrations in receiving waters under several scenarios. Bioaccumulation in lower trophic level consumer organisms (bivalves) is projected from a likely range of concentration, partitioning, and speciation scenarios using pathway bioaccumulation models. Comparisons of Se concentrations in Bay-Delta clams are made to proposed protective dietary Se guidelines for fish and birds. Selenium concentrations in a few key predators are predicted from correlations with bivalve tissue concentrations of Se using data from the existing literature. Because the relation between tissue concentrations and adverse effects are relatively well constrained for Se in wildlife, predictions of tissue residues in waterfowl and fish provide a first order estimate of potential adverse effects of Se mass emissions. The specific information—bioaccumulation of Se by clams and biotransfer of Se to fish and waterfowl—could be applied to evaluate proposals for disposal of Se from the SJV that include discharge to aquatic systems (i.e., using the Bay-Delta as a receiving water). Presentation of the process by which we evaluate the ecological effects of Se is as important as the specifics of the discussion as applied to the Bay-Delta. The general process of a linked bioaccumulation model using a bioindicator organism to assess potential adverse impacts on predators can be applied to other ecosystems subjected to Se loading and can help in the development of national or site-specific Se criteria for aquatic protection.

Generic Selenium Issues

Existing knowledge concerning the biogeochemistry of Se allows the following generalizations:

1. Geologic sources of Se are widespread (Figure 1).
2. Exploitation of energy sources (oil and coal), mining of phosphate ore, irrigation of areas underlain by organic-rich marine shales, and irrigation of lands where alluvium is derived from

such shales, mobilize geologic Se and ultimately result in the contamination problems found today (see examples in Figure 1).

3. Linked biological and geochemical reactions affect the form of Se (Figure 2). Geochemical form (speciation) determines how readily the element enters aquatic food webs, initiates food web transfer, and cycles through particulate matter, sediments, consumer organisms, and predators.
4. Hydrologic connections also determine the effects of Se. Compartmentalized ecological systems can interact at critical hydrologic junctures such as in estuaries. Seemingly harmless concentrations of Se in a riverine system may become problematic in downstream impoundments, marshes, or wetlands, where cycling and bioaccumulation are accentuated (Luoma et al., 1992; Skorupa, 1998a; Lemly, 1999b). The geographic scale of Se issues can extend beyond local conditions and therefore, an analysis of downstream effects needs to follow.
5. Traditional toxicity tests are problematic because they determine toxicity only via direct water-borne exposures. Direct transfer of Se from solution to animals such as fish and bivalves is a small proportion of exposures. Bioaccumulation and uptake via food is the most important route of Se transfer to upper trophic level species (Figure 2) (Ohlendorf et al., 1986; Saiki and Lowe, 1987; Presser and Ohlendorf, 1987; Lemly, 1985; Luoma et al., 1992; Presser et al., 1994).
6. Selenium efficiently bioaccumulates through aquatic food webs, and strongly biomagnifies into many components of the food web (Saiki, 1986; Presser and Ohlendorf, 1987; Luoma et al., 1992; Maier and Knight, 1994). Invertebrates may be the best indicator for monitoring predator exposure. Consumer species like bivalves integrate the influences of environmental concentrations, speciation, and transformations of Se and are practical to sample. Predators, on the other hand, are mobile and impractical to sample in large numbers on a routine basis. A predator’s choice of food, which varies widely among species, could result in some trophic pathways being more efficient accumulators of Se than others (Lemly, 1982; 1985; Luoma, et al., 1992; Luoma and Fisher, 1997; Skorupa, 1998a; CH2M HILL, 1996; 1999a).
7. Charismatic species (birds and fish) are the first to express the effects of Se contamination due to this efficient bioaccumlation in the food web and their sensitivity to exposure to Se (Ohlendorf, 1989; Ohlendorf et al., 1989a; Hamilton et al., 1990; Lemly, 1996b**;** c; Skorupa,

1998a; b; c; Hamilton et al., 2000a; b). Thus, bioaccumulation models must link food sources to predator animals to predict biotic effects.

8. Selenium is a strong reproductive toxin in birds and fish when it is present in sufficient concentrations in their food (see reviews in Skorupa, 1998b and Hamilton et al., 2000a). In contrast to many other contaminants, significant environmental damage due to Se contamination has been well documented. Skorupa (1998a) described case studies showing different degrees of Se effects in a variety of wetlands and reservoirs impacted by agricultural drainage, burning of fossil fuels, or refining of oil. An especially well documented case study exists for Belews Lake in North Carolina where Se contamination resulted in local extinctions of most fish populations, via reproductive impairment and teratogenesis (Cumbie and Van Horn, 1978; Lemly, 1985; 1997a). The most well known case of Se poisoning in a field environment was at Kesterson National Wildlife Refuge in the SJV of California (Ohlendorf, et al., 1986; Presser and Ohlendorf, 1987; Skorupa and Ohlendorf, 1991). There, teratogenesis and reproductive failure were widespread in populations of water birds.
9. Although extreme Se contamination causes death in adult organisms, the responses of greatest concern are impairment of reproductive success (e.g. failure of eggs to hatch) and teratogenesis (deformities in juveniles) in birds and fish (Skorupa and Ohlendorf, 1991). Inhibition of growth, depressed immune system response, mass wasting, and winter stress syndrome also are effects of concern (Ohlendorf, 1989; Lemly, 1993b; 1998a; CH2M HILL, 1997; 1999b; USFWS and NMFS, 1998 and amended, 2000; Santolo et al., 1999). Reproductive damage and teratogenesis can occur at low concentrations [low micrograms per liter (μg/L)] of environmental Se because the window is narrow between the amount of Se that is nutritionally beneficial and the amount that is toxic (Wilber, 1983; National Research Council, 1976; USEPA, 1980; 1998; Haygarth, 1994; Skorupa, 1998a; b). Data exist that relate teratogenesis, hatchability, and reproductive success to Se concentrations in food, avian eggs, and fish larvae (reviews in Heinz, 1996; Lemly, 1998b; Maier and Knight, 1994; Skorupa, 1998a; b). Ecological risk thresholds and a risk index based on Se concentrations in water, sediment, and tissue are currently under debate (Peterson and Nebeker, 1992; Engberg et al., 1998; Lemly, 1995; Skorupa, 1998a; b; c).
10. Uncertainty exists in the USEPA Se criteria for the protection of aquatic life, especially for criteria derived from water-only, short-term exposure of surrogate species. Uncertainty also

exists for criteria derived using limited field data on food chain exposure, because few studies were available at the time of promulgation (USEPA, 1992; 1998). The toxicity-testing database does not consider bioaccumulation, although bioaccumulation from food determines the ecological effects of Se. A Se criterion derived primarily from food web exposure would be more relevant to field conditions in aquatic systems.

11. Effects of Se on human health are of concern. State human health advisories have restricted consumption of edible fish and birds and eliminated consumption for children and pregnant women when Se concentrations exceed a certain criterion [California Department of Fish and Game (CDFG), 1985; 1986; 1988, all on-going; 1987; Fan et al., 1988; SJV Drainage Program, 1989; 1990b].
12. No satisfactory chemical, physical or biological treatment technology yet exists to remove Se contamination from irrigation drainage waters (Hanna et al., 1990; Hansen et al., 1998; SJV Drainage Implementation Program, 1999a; b; c; d). Treatment technologies that work on small effluent streams are inefficient and expensive to employ on large volumes of contaminated water (SJV Drainage Program, 1990a; SJV Drainage Implementation Program, 1998; National Irrigation Drainage Program, 2000). Treatment technologies still being tested are flow-through wetlands and biological precipitation (Hansen, et al., 1998; SJV Drainage Implementation Program, 1999a), even though large-scale biological treatments have generated serious ecological problems (Presser and Piper, 1998; Skorupa, 1998a). A management plan specific to the arid western SJV has demonstrated through in-depth studies that comprehensive and systematic implementation of components, such as source control and land fallowing, can reduce the amount of drainage generated and substantially contribute to the eventual resolution of the drainage problem (SJV Drainage Program, 1990a).

Selenium Issues in the Bay-Delta

The surface and ground waters of the SJV are part of a complex, hydrologic system that extends from the riparian wetlands of the Sacramento River and SJR through the Bay-Delta to the Pacific Ocean (Presser and Piper, 1998) (Figures 3 and 4). This natural system provides the framework for the Central Valley Project (CVP) which is a massive engineered complex of dams, off-stream storage reservoirs, pumping facilities, irrigation and drinking water supply canals, and agricultural irrigation drainage canals [U.S. Bureau of Reclamation (USBR), 1984a]. Figure 5 presents a detailed schematic of the hydrologic connections of the SJV (Figure 3) to the Bay-Delta (Figure 4) including the Sacramento River and SJR. The sustainability of the balance and quality of water in this system are crucial to the welfare of California, especially to the arid SJV.

Selenium issues are of special concern within the Bay-Delta ecosystem because:

1. Selenium contamination exists under present conditions in the Bay-Delta from known sources of Se within the estuary and in watersheds draining to the estuary. Watershed sources are linked to SJV farmland activities where irrigation of salinized soils has led to proposed management alternatives to sustain agriculture by draining salts and Se collected as subsurface drainage to the Bay-Delta via the SJR or SLD [e.g., CSWRCB, 1985; SJV Drainage Program, 1990a; Presser and Ohlendorf, 1987; Presser and Piper, 1998; Skorupa, 1998a; California Central Valley Regional Water Quality Control Board (CCVRWQCB), 1998a; b; USFWS and NMFS, 1998 and amended 2000). Proposals for construction of a collector drain and an extension of the existing SLD to remove salts and Se from the SJV have been under consideration for approximately 50 years (Table 1). Water quality in the SJR has degraded significantly since the 1940's because of disposal of agricultural wastewater from the SJV (CCVRWQCB, 1995). Even though the SJR is a source water for the Bay-Delta, selenium sources and contamination within the North Bay (i.e., Suisun Bay and San Pablo Bay) have been linked in the past mainly to oil refineries discharging waste from processing Se-enriched crude oil from the SJV and adjacent Coast Ranges (e.g., White et al., 1987; 1988; 1989; Cutter, 1989; Johns, et al., 1988; Cutter and San Diego-McGlone, 1990; Urquhart and Regalado, 1991; San Francisco Estuary Project, 1991; 1992; Luoma, et al., 1992; Brown and Luoma, 1995a; Luoma and Linville, 1997; Linville and Luoma, in press; USFWS and NMFS, 1998 and amended, 2000).
2. Selenium contamination documented from 1982 to the mid-1990's was sufficient to threaten reproduction (> 10 μg Se/g in tissue) in key species within the Bay-Delta estuary ecosystems (Table 2) [White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991; San Francisco Estuary Project, 1991; 1992; Harvey et al., 1992; California San Francisco Bay Regional Water Quality Control Board (CSFBRWQCB), 1992a; b; 1993; Brown and Luoma, 1995a; Linville and Luoma, in press]. The most severely threatened species appear to include, but are not restricted to white sturgeon (*Acipenser transmontaus*), Sacramento splittail (*Pogonichthys macrolepidotas*), starry flounder (*Platichthys stellatus*), Dungeness crab (*Cancer magister*),

surf scoter (*Melanitta perspicillata),* greater scaup (*Aythya marilla),* and lesser scaup *(Aythya affinis*) (Ohlendorf et al., 1986; White et al., 1987; 1988; 1989; Ohlendorf et al., 1989b; c; Urquhart and Regalado, 1991; Luoma et al., 1992; USFWS, 1995; Hothem et al., 1998). In 1989-1990 in the North Bay, average Se concentrations in surf scoter liver samples exceeded the threshold level for avian reproductive toxicity (Heinz, 1996) by eight-fold and in sturgeon flesh samples exceeded the threshold for effects in fish (Lemly, 1998b) by two-fold. Currently, populations and catches per unit effort (where applicable) of all the predator species mentioned above are in decline. A number of causative factors may be involved (CALFED, 1998a; b; 1999a; b; c; d; USFWS and NMFS, 1998 and amended, 2000), but because of the exceedance of Se thresholds for adverse effects in tissue of prey and predators, Se cannot be excluded as one.

3. Some food webs in the Bay-Delta may be particularly vulnerable to moderate Se contamination. Analyses in 1982-1996 showed that the animals with the highest Se tissue concentrations from the North Bay (i.e., Suisun Bay, Carquinez Strait, and San Pablo Bay) ingested bivalves (*Corbicula fluminea* prior to 1986 and *Potamocorbula amurensis* in subsequent samplings) as a major component of their diet. Selenium concentrations in the predominant bivalve in the Bay-Delta were higher in the mid-1990's (Linville and Luoma, in press) than in 1977 through 1990 (White et al., 1987; 1988; 1989; Cutter, 1989; Johns et al., 1988; Urquhart and Regalado, 1991), partly because a new species (*P. amurensis*) had become predominant in the Bay-Delta. The specific bioaccumulation pathway from sediment and benthic/suspended biomass to bivalves to predators (bottom feeding fish, diving ducks, and Dungeness crab) may be the most important route of Se transfer to the upper trophic levels in the estuary. Levels in *P. amurensis* reached 20 μg Se/g dry weight (dw) in the North Bay in October 1996, exceeding two-fold the toxicity threshold in food for predators (> 10 μg Se/g dw) that result in adverse effects.

4. Portions of the Bay-Delta and the SJR are currently listed by the state as being subjected to contamination from a suite of chemicals (e.g., mercury, diazinon, PCBs, dioxin, PAHs, and Se) (CCVRWQCB, 1994a; 1998b; CSWRCB, 1999b; c). State or federal criteria have been exceeded in these listed waterbodies, causing adverse aquatic life and human health impacts (e.g., Fairey et al., 1997; Davis et al., 1997; Dubrovsky et al., 1998). Portions of the SJR are

designated as *water-quality limited* due to Se. Most recently, portions of the Bay-Delta have been listed as *known toxic hotspots of high priority* due to Se.

5. The amount and quality of the wetlands in the Bay-Delta leaves in doubt the future status of many wildlife populations (Harvey et al., 1992; CALFED, 1998a; b; San Francisco Estuary Project, 1999); Se contamination affects the quality of the already limited acreage of wetlands and other crucial habitat (CALFED, 1998a; b and 1999a; b; c; d). A recovery plan was deemed necessary for Sacramento/San Joaquin Delta native fishes (USFWS, 1995). The plan includes designation of critical habitat (i.e., slight changes in habitat condition may cause large changes in population status) for Delta smelt (*Hypomesus transpacificus*), a threatened species (58 Federal Register 12854). Critical habitat for the threatened Sacramento splittail (*Pogonichthys macrolepidotas)* (64 Federal Register 5963) is not currently designated.
6. Environmental safeguards were enacted after the ecological disaster at Kesterson National Wildlife Refuge, but many may be inadequate for the specific problems of the Bay-Delta. For example:
   a) The USEPA criterion for the protection of aquatic life (5 μg Se/L) is not in effect for upstream inflows to the Bay-Delta (i.e., the SJR and its tributary sloughs) due to state postponements of compliance until 2010 (USEPA, 1992; CCVRWQCB, 1996d). Selenium concentrations in the river have exceeded USEPA criteria (50% of the time for the period 1987 to 1997 at Crows Landing, Figures 3 and 5) since the discovery of Se effects at the Kesterson National Wildlife Refuge (CCVRWQCB, 1996a; b; 1998f). Load limits enacted by the state in 1996 were exceeded in 1996 through 1998. Impacts from Se on the SJR have not been directly evaluated partly because no program systematically collects biological, water quality, and flow data (Presser et al., 1996; Presser and Piper, 1998). An aquatic hazard assessment of a tributary slough receiving the greatest impact from agricultural drainage found the Se hazard as "high" (Lemly, 1995; 1996a; USBR et al., 1998; 1999). Replacement of native species of varying tolerance in the SJR has led to a rating of "poor" on the index of biological integrity (Moyle et al., 1986) for river sites above and below drainage discharges. Populations of fish in the SJR and adjacent sloughs are now dominated by introduced species having broad environmental tolerances (USBR et al., 1998; 1999). The role of Se in these changes is not proven, but effects on native fish

populations are documented elsewhere (e.g., Lemly, 1997b; Hamilton, 1998; 999; and Hamilton et al., 2000a).

b) Refinery inputs to the Bay-Delta have declined since 1998. State waste discharge permits limit oil refinery effluents based on Se loads. Effluents, however, may reach a daily maximum of 50 μg/L Se, which is ten times above the promulgated USEPA criterion (CSFBRWQCB, 1992b; USEPA, 1987 and 1992). It is expected that food web contamination attributable to the refineries will decline; dilution of the effluent discharges by low Se inflows is critical. In 1995, deformed embryos were found in 30% of mallard (*Anas platyrhynchos*) nests and in 10% of American coot (*Fulica americana*) nests at a marsh used for Se remediation in the North Bay receiving a refinery effluent of 20 μg Se/L (without dilution) (Skorupa, 1998a).

c) Selenium concentrations were below all promulgated water quality protection guidelines (2 to 5 μg Se/L) in both the Delta and the Bay in all surveys of the Bay-Delta from 1982 to the mid-1990's (Cutter, 1989; Cutter and San Diego-McGlone, 1990; Cutter et al., in preparation). Nevertheless, Se in the food web was sufficient to be a threat to some species and a concern to human health if those species were consumed (CDFG, 1988 and on-going; Fan et al., 1988; SJV Drainage Program, 1990b; CSFBRWQCB, 1992a; b).

d) A biological opinion and formal consultation by the USFWS and NMFS (1998 and amended, 2000) on USEPA's proposed California Toxics Rule (*Proposed Rule for the Promulgation of Water Quality Standards: Establishment of Numeric Criteria for Priority Toxic Pollutants for the State of California, 1997 and amended, 2000*) found that the USEPA criterion for Se jeopardizes several Bay-Delta or SJR fish [Delta smelt (*Hypomesus transpacificus*), Sacramento splittail (*Pogonichthys macrolepidotus*), steelhead trout (*Oncorhynchus mykiss*) and chinook salmon (*Oncorhynchus tshawytsch*], birds [California light-footed rail (*Rallus longirostris levipe)*, California clapper rail (*Rallus longirostris obseletus*), California least tern (*Sterna antillarum browni*), and marbled murrelet (*Brachyramphus marmoratus*)] and amphibians/reptiles [giant garter snake (*Thamnophis gigas*), and California red-legged frog (*Rana aurora draytonii*)] that are presently endangered or proposed threatened species (Endangered Species Act, 1973). The agencies recommend a 2 μg Se/L chronic criterion for protection of aquatic life for all waters within range of the listed species to aid in their survival and recovery in critical habitats.

e) State permits for Se discharges to private evaporation ponds used for agricultural drainage disposal are limited only to a Se hazardous waste criterion of 1,000 μg Se/L (California Code of Regulations, 1979 and as amended). These ponds, in the Tulare basin of the southern SJV, are located in part of the Pacific Flyway heavily used by migratory birds. A state health hazard warning for consumption of American coot was posted for a 16-pond area in 1987 (CDFG, 1987; SJV Drainage Program, 1989; 1990b). A 10-50% rate of embryo teratogenesis was documented during the period 1987 to 1990 (Skorupa, 1998a; b). An attempt to regulate evaporation ponds on the basis of field observations of bird impacts was not adopted in lieu of altering drainage evaporation ponds to limit bird-use (i.e., "bird-free" ponds) and provision of compensatory and alternative wetland habitat (CSWRCB, 1996a). Deformed birds also were found in 1996 at a constructed solar evaporation pond used as part of a drainage reduction plan. The incidence of teratogenesis in black-necked stilt (*Himantopus mexicanus*) (56.7%) was the highest ever reported (Skorupa, 1998a).

f) Federal (40 CFR 131.12) and state (CCVRWQCB, 1994a; 1996a) anti-degradation policies may apply to the impaired water quality segment of the SJR or the groundwater aquifers of the SJV. In addition to the degradation of the SJR noted above, mobilization of Se by irrigation and contamination of ground water have resulted in concentrations of Se greater than 1,000 μg/L Se (a hazardous waste; California Code of Regulations, 1979 and as amended) in some aquifer locations of the SJV (Deverel et al., 1984).

8. Human health advisories against consuming Se-contaminated edible tissue of fish [bluegill (*Lepomis macrochirus*) and largemouth bass (*Micropterus salmodes*)] and birds (ducks and coots) are presently posted for the SJV (CDFG, 1985 and on-going; 1986 and on-going; Fan et al., 1988; SJV Drainage Program, 1990b). Advisories also exist for eating birds (scoter and scaup) from the Bay-Delta (CDFG, 1988 and on-going). The advisories are issued when Se concentrations in flesh reach or exceed 2 μg/g wet weight [6-12 μg/g dw, assuming 65-85% moisture] (SJV Drainage Program, 1990b; Saiki et al., 1991) and restrict human consumption to not exceed 112 grams of flesh per one- or two-week period or 20 grams of fish or bird muscle per day in addition to the regular daily intake (Fan et al., 1988). Children and pregnant women are advised not to consume any game from the posted areas.

9. Important gaps also occur in existing knowledge (Luoma and Fisher, 1997; Clements, 2000). Most Se studies have taken place in wetlands and in freshwater reservoirs. There is a deficit of

knowledge about the fate and effects of Se in estuarine environments similar to the Bay-Delta, and important data gaps exist for specific regions of the Bay-Delta. Many of the processes and mechanisms that determine Se impacts may be known generically, but are less well known in the Bay-Delta. On the other hand, knowledge of some of the most complex processes—influences of speciation, mechanisms of bioaccumulation, food web transfer, and effects on predators—is probably better known for Se than for many other contaminants.

In this paper we primarily:

- describe Se issues and their history in the SJV, the SJR, and the Bay-Delta;
- project potential loading of Se from the western SJV resulting from engineering solutions and management alternatives proposed historically;
- detail the state of knowledge of the processes that determine the fate and effects of Se released to the Bay-Delta;
- summarize existing knowledge concerning Se contamination in the Bay-Delta ecosystem;
- characterize existing knowledge for each set of processes that link loads and effects;
- forecast concentrations, form, bioaccumulation, trophic transfer, and effects of Se on predators for several load scenarios; and
- define research needs and actions that might help narrow the uncertainties about proposed discharges of Se to aquatic ecosystems.

Selenium inputs to the Bay-Delta are changing, or could be changed, by activities expected to occur within the Bay-Delta and in the SJR/SJV watershed (see specific listing in next section). Forecasts of the effects of such changes are essential to a holistic, successful restoration or rehabilitation of the Bay-Delta. Scientific data and models are necessary to develop such forecasts.

ISSUES ARE CHANGING

The probability is high that inputs of Se to the Bay-Delta via the SJR or an artificial conveyance such as the SLD will increase in the future. The SJR is the only current means (i.e., the only natural channel) by which Se and salts can be removed from the SJV. The SJR is hydrologically connected to the Bay-Delta, but recycling back to the SJV occurs via the Delta-Mendota Canal. Changes in Se discharges to the SJR will be manifested in these downstream receiving waters (i.e., south Delta, Suisun Bay, Carquinez Strait, San Pablo Bay) to the extent that those waters are managed so that they reach the downstream estuary ecosystems.

Existing policies for the western SJV are probably not sustainable [Wanger, 1994; Stevens and Bensing, 1994; CSWRCB, 1997 and 1999a; d; Westlands Water District (WWD), 1996; 1998; U.S. House of Representatives, 1999; Hug et al., 2000]. Soil and ground water quality are deteriorating in un-drained lands (SJV Drainage Implementation Program, 1998); disposal sites of sufficient scale for collected drainage (e.g. at Kesterson National Wildlife Refuge and Tulare Basin evaporation ponds) have resulted in adverse ecological effects (Skorupa, 1998a). Effects of several disposal options for drainage have long been discussed, environmental impact reports prepared, and engineering studies of the problem made (Table 1) [e.g., USBR, 1962; California Department of Water Resources (CDWR), 1965a; b; 1969, and 1974; USBR, 1978; SJV Interagency Drainage Program, 1979a; b; Brown and Caldwell, 1986; SJV Drainage Program, 1990a; SJV Drainage Implementation Program, 1998). As discussed later in more detail (also see Appendix A**)**, many studies of Se contamination have provided insufficiently holistic evaluations of the problem. These studies do not adequately account for linked factors that determine effects of Se on the aquatic food web and higher trophic levels.

Salinization and Se contamination issues in the western SJV ultimately stem from the geologic setting, an imbalance in the hydrologic cycle, and clay layers impeding drainage (SJV Interagency Drainage Program, 1979a; CH2M HILL, 1988; SJV Drainage Program, 1989; 1990a). High evaporation rates in the semi-arid climate cause salinization of valley soils; the salts are rich in Se because of the geologic origin of the soils. Salt build-up will inevitably reduce agricultural potential. Irrigating soils and draining the irrigation waters into buried, perforated pipe help alleviate salinization. This drain water is then collected, and transported to a disposal site. The waters draining from the saline soils are not only elevated in salts, but are especially elevated in Se (Presser and Ohlendorf, 1987). Where drainage has been halted, Se is accumulating in the internal reservoir of ground water in the SJV (SJV Drainage Program, 1990a; SJV Drainage Implementation Program, 1998; WWD, 1996; 1998). The accumulation of salts and contaminants in ground water will, eventually, impede beneficial use of this resource (CSWRCB, 1985; 1987; 1994; 1999a; d; CCVRWQCB, 1988; 1996a; 1998b). Where drainage water is being collected, its disposal results in increases in Se contamination of surface water resources, with possible effects on ecological integrity (see mandated environmental reviews for proposed SLD in 1965, 1975, 1977, 1979, 1981, 1984, 1985, 1987, 1991, 1994, and 1999, Table 1).

No feasible engineering solutions yet exist for treating irrigation drainage to remove Se from the water-column, at least not at the scale necessary to alleviate the problem of waste disposal (Hanna, et al., 1990; SJV Drainage Program, 1990a; SJV Drainage Implementation Program, 1999a).

In August 1999, the California State Water Resources Control Board (CSWRCB, 1999d) held an agricultural drainage discharge workshop in which it was decided to go forward with a memorandum of understanding that would begin permit applications and environmental documentation for a master drain (i.e., an extension of the SLD) to remove salts from the western SJV. As in earlier proposals, the final point of discharge of this drain was the Bay-Delta. This action was an effort to seek relief for California farmers. Environmental groups remain opposed to studying the drain as an alternative solution to source control implemented through a number of measures including water conservation, drainage reuse, and land retirement (i.e., cessation of irrigation in areas of elevated Se concentrations in shallow ground water). Nevertheless, during the next few years, federal and state agencies may be required to evaluate proposals and discharge permits that could significantly change Se inputs to the Bay-Delta. Particularly affected would be the SJR watershed, the south Delta, and the North Bay, which includes Suisun Bay and San Pablo Bay (Figures 3 through 5).

The proposals could include the following:

- As stated above, a 100-mile extension of the existing SLD is being proposed to alleviate the build-up of salts in agricultural soils and the aquifers of the western SJV by removing salts from the valley. The SLD would convey subsurface agricultural drainage from the western SJV to a discharge point near Chipps Island in Suisun Bay (Figures 4 and 5). This extension of the SLD would result in increased Se loading to the Bay-Delta.
- Current projects allow discharge of agricultural drainage into the SJR. Renewals are underway of the federal agreement and state permit to allow an existing 28-mile section of the SLD to convey subsurface agricultural drainage to the SJR. Load targets and management alternatives are under negotiation. A net increase or an increase during some months (i.e., during high flows) in Se discharges to the SJR is possible in the future. These Se loads discharged from this *de facto* drain could reach the Bay-Delta under some types of river discharge and management scenarios.
- In response to state regulated salinity objectives and USEPA's regulation of non-point source pollution through TMDLs (Total Maximum Daily Loads), real-time dilution of salt, Se, boron or dissolved oxygen could occur in portions of the SJR. This approach would change the

amount and timing of Se loading to the Bay-Delta (CCVRWQCB, 1994b; 1996a; 1998a; CSWRCB, 1997; 1999a; USEPA, 2000) as loads are integrated with flows.

- Linked to the above issue is proposed restoration of the SJR by increasing flows in the river to aid fish passage (National Resources Defense Council et al., 1988; CALFED, 1999a; URS Greiner Woodward Clyde, 2000).
- Changes in Se inputs will also be influenced by decisions about drainage of salts from the SJV. A recent state water right decision requiring the USBR to meet salinity objectives at Vernalis on the SJR and at three locations in the interior of the southern Delta (CSWRCB, 1994; 1997; 1999a; EA Engineering, Science and Technology, 1999) and a state program aimed at salt reduction (CCVRWQCB, 2000a) will affect management alternatives. Currently, the salinity objectives adopted in 1991 are violated most months of the year (67 to 78 % from 1986 to 1998).
- Physical changes in water management could result in greater inflows into the Bay-Delta from the Se-laden SJR. The 1994 Bay-Delta Water Accord (CSWRCB, 1994) mandated greater inflows to the Bay-Delta from the SJR. Inflows of Se from the SJR have traditionally been small compared to other sources (Cutter, 1989; Cutter and San Diego-McGlone, 1990; Johns et al., 1988), because most of the flow of the SJR was recycled back through the Delta-Mendota Canal to the SJV before it reached the Bay-Delta (Figures 3 and 5). Changes in water management could reduce recycling and thus increase throughput to the Bay-Delta.
- Construction of an isolated conveyance facility (a Peripheral-Canal-like water conveyance alternative) or modifications of current diversion and export channel dimensions could also result in an exchange of Sacramento River inflow for SJR inflow to the Bay-Delta (CALFED, 1998a; b). Any activity that results in more SJR inflow entering the Delta or Bay will result in more Se input to areas that are part of the recently enacted Bay-Delta Ecosystem Restoration Plan (CALFED, 1998a; b and 1999a; b; c; d).
- Refineries have reduced their Se discharges due to mass emissions reduction regulations (Table 2) (CSFBRWQCB, 1992a; b; 1993). In July 1998 refineries were required to meet the goals set by the CSFBRWQCB (1996; 1997). This means that concentrations of at least some forms of Se (i.e., selenite) in the Bay-Delta are decreasing (Cutter et al., in preparation), and that the predominant cycling pathways could change. In Belews Lake, North Carolina, for example

(Lemly, 1997a), exposures of fish to Se changed from water column-based pathways to sediment-detrital pathways after sources were eliminated.

- Refinery Se was dominated by selenite; Se from the SJV is dominated by selenate, with some apparent conversions to organo-Se in receiving waters (Cutter, 1989; Cutter and San Diego-McGlone, 1990, CSFBRWQCB, 1992a; b; 1996; 1997). Thus the predominant biogeochemical transformation pathways and bioavailability of Se could change as the predominant sources to the Bay-Delta change.
- Changes in residence times of water in the south Delta and the North Bay could result from changes in water management. For example, greater diversion of water (another possible outcome of changes in water management) could result in increased residence times in the Bay-Delta during some times of year. Mean hydraulic freshwater residence times in Suisun Bay were estimated at 0.5 days during periods of high flow and at 35 days for period of low flow (Walters et al., 1985). Longer hydraulic residence times seem to be associated with greater Se contamination in the food web (Lemly, 1997a; Zhang and Moore, 1997a; Skorupa, 1998a).

Biological changes also are occurring in the ecosystem, and some of these appear to affect Se cycling. These changes include:

- The dominant consumer organism in the Bay-Delta changed with the invasion of the Asian clam *Potamocorbula amurensis* in 1986 (Nichols et al., 1986; Carlton et al., 1990; Brown and Luoma, 1995b). It is possible that this species is especially efficient at bioaccumulating Se, although studies directly addressing the mechanisms of Se bioaccumulation by *P. amurensis* are not yet complete (Brown and Luoma, 1995a; Luoma and Linville, 1997; Linville and Luoma, in press). Invasion of this species was helped by a depauperate benthic community in mid-1986 and the complexities of salinity gradients and hydraulic residence times present in the North Bay (Cloern and Nichols, 1985; Peterson et al., 1989; Nichols et al., 1986).
- One implicit goal of a successful restoration is to develop a more complex, native species-dominated food web (CALFED, 1998a; b and 1999a; b; c; d). Selenium might bioaccumulate more efficiently through more complicated food webs (a question under study), which raises the question of the compatibility of existing or greater levels of Se contamination with restoration goals.

- The cause of the declines of some key species in the Bay-Delta (e.g. white sturgeon, Sacramento splittail, starry flounder, surf scoter) may include Se effects on reproduction and ultimately, survival of the population. Increased Se in the Bay-Delta could increase that threat.
- Marsh restoration in the Bay-Delta, if accompanied by increased Se discharges, could result in trapping and recycling of increased quantities of Se in the system, with the possibility of greater Se contamination in some species. Under the worst scenarios, it is conceivable that management of concomitant issues—water and salt management—rather than Se contamination could create another ecological crisis in the Bay-Delta similar to that created at Kesterson National Wildlife Refuge.

Refinements of Se water quality criteria, especially for the Bay-Delta, also are likely. The current USEPA promulgated national Se chronic criterion for the protection of aquatic life (5 µg Se/L) is based upon bioaccumulation-related toxicity observed in Belews Lake and Hyco Reservoir (USEPA, 1987 and 1992). The USFWS recommends a criterion of 2 µg Se/L, based upon a series of case studies of Se contamination and effects on birds in western wetlands (Skorupa, 1998a; USFWS and NMFS, 1998 and amended 2000). The Canadian criterion for wildlife protection is 1 µg Se/L (Environment Canada/Health Canada, 1995; Outridge et al., 1999). The technical limitations of the basis for the existing water quality criteria raise questions about their suitability as the sole standard to assure protection of the Bay-Delta. As stated previously, Se concentrations were below all recommended guidelines in both the Delta and the Bay in the latest surveys in 1996. Nevertheless, Se in the food web was sufficient to be a threat to some species and a concern to human health if those species were consumed (Table 2) (Linville and Luoma, in press; CDFG, 1988 and on-going; Fan et al., 1988; CSFBRWQCB, 1992a; b). The Bay-Delta is probably best suited for site-specific Se guidelines, but the details of such guidelines have yet to be identified.

APPROACH TO UNDERSTANDING CHANGING ISSUES

In this evaluation of Se issues we systematically describe the linked factors that determine effects of Se on aquatic food webs and higher trophic levels (see conceptual model, Figure 2). This holistic approach to the issue differs from earlier attempts to skip links in tying waterborne Se to the effects of the element. We propose that the holistic approach offers opportunities to more accurately project ecological effects from loads and to identify resolutions of the difficult questions involved. The steps that are considered include:

- *Projecting loads from the potential sources of Se*. Selenium loads projected from available data on concentration and drainage volume provide the basis for determining the upper and lower limits of Se discharge from the western SJV that can be expected to enter the Bay-Delta via either a proposed direct conveyance to the Bay-Delta or the SJR. Analyzing the annual, monthly, daily, and hourly variability of Se loading is necessary to address trends and patterns in discharges. The accuracy of Se load calculations on any time-scale is dependent on the number and frequency of the measurements taken to determine flow and Se concentration (Presser et. al., 1996). Large uncertainties are associated with data compiled for annual average loads of Se from agricultural and natural sources. Annualized, generalized averages of concentration, flow, and load hide infrequent samplings, sampling that does not reflect flow-dependent concentration changes, or spatially dispersed samplings. Annual average data used here, although documented as to source and type (see Appendices A through D), should be used with caution and are applied here to obtain ranges of projected Se loads.
- *Identifying implications of the modes of conveyance* that determine transport of those Se loads to the Bay-Delta. A SLD extension or the SJR are the most likely modes of conveyance (Figures 3 and 5). The SJR was mostly recycled during the period when studies of Se were conducted in 1986 to 1990, so little Se reached the Bay-Delta from this source. The passage of SJR inflows into and through the Delta is not well known at present, but hydrologic models exist that can be used as frameworks for future modeling (e.g. Cheng et al., 1993; Monsen, 2000). Throughput of SJR inflows could be influenced by changes in water management to aid fish passage including construction of elaborate Delta barriers and scheduling of flushing flows. If a SLD extension is constructed to Chipps Island in the Delta (Figures 4 and 5), Se and salts from the soils of the SJV would be released directly into the Bay-Delta.
- *Identifying effects of projected loads on concentrations in receiving waters*. Loads and seasonal variability in Sacramento River and SJR discharges are critical considerations in determining concentrations in the Bay-Delta.
- *Identifying changes in and implications of biogeochemical speciation of Se and biogeochemical transformations of Se between dissolved and particulate forms*. Speciation of Se is critical in that it drives routes and efficiency of transformation of Se from dissolved to particulate forms.

Understanding particulate Se and its speciation cycle is critical in determining biological effects.

- *Incorporating factors controlling the bioavailability and biotransfer of Se to macroinvertebrate primary consumers under the different concentration and speciation conditions*. Bioaccumulation of Se is primarily determined by the form and concentration of particulate Se (food).
- *Determining exposure of sensitive predators from projected Se concentrations in invertebrate and vertebrate prey in the Bay-Delta ecosystem*. Existing data from 1988 to 1999 for Se concentrations in bioindicator clams show elevated levels compared to uncontaminated reference areas (Johns et al., 1988; Brown and Luoma, 1995a; Luoma and Linville, 1997; Linville and Luoma, in press). Exposure of predators is determined by the level of bioaccumulated Se in these prey organisms (CSFBRWQCB, 1992a; b; 1993; 1996; 1997).
- *Estimating effects of Se on predators from tissue residues*. Adverse effects have not been demonstrated in predators in the Bay-Delta primarily because of the complexity of reproduction in the most affected species (Conomos, 1979; Conomos et al., 1985; Nichols et al., 1986; Davis et al., 1991; Harvey et al., 1992; Monroe et al., 1992; and USFWS, 1995). Many threatened species are not resident in the system all year. Through 1996, both Se concentrations in tissue of predators and in their food pointed to threats to the reproductive health of the predators (White et al., 1987; 1988; 1989; Cutter, 1989; Johns, et al., 1988; Cutter and San Diego-McGlone, 1990; Urquhart and Regalado, 1991; San Francisco Estuary Project, 1991; 1992; CSFBRWQCB, 1992a; b; Luoma et al., 1992; Brown and Luoma, 1995a; Luoma and Linville, 1997; Linville and Luoma, in press). However, such estimates of risk are derived from laboratory and field studies conducted elsewhere (USEPA, 1998; Lemly, 1993a; 1995; 1996a; 1998a; Skorupa, 1998a; Engberg et al., 1998).

For each of the above factors, we define the principles that govern its influence and describe the existing knowledge for the Bay-Delta.

SOURCES

The major sources of the Se in the Bay-Delta are (Figures 4 and 5):

- discharges of irrigation drainage conveyed from agricultural lands of the western SJV via the SJR or potentially from an extension of the SLD;
- effluents from the North Bay refineries which refine crude oil from the western SJV along with crude oil from other sources;
- Sacramento River inflows which is the dominant freshwater inflows (high water volume) to the Bay-Delta; and

Effluents from Bay-Delta wastewater treatment plants and industries other than refineries are minor sources of Se (Cutter and San Diego-McGlone, 1990) and will not be considered further.

Inputs of Selenium from Agriculture in the Western San Joaquin Valley

The problem

The Coast Ranges, which border the SJV on the west, are composed of marine sedimentary rocks that are enriched in Se (Figures 3 and 5) (Presser and Ohlendorf, 1987; Presser et al., 1990). An internal reservoir of salt (and by inference Se) has accumulated through 1.0 to 1.2 million years within the SJV soils and aquifers as a result of runoff and erosion from the Coast Ranges (Bull, 1964; Milam, 1985; McGuire, 1988; Deverel and Gallanthine, 1989; Gilliom et al., 1989; Presser et al., 1990; Presser et al., 1994; Presser, 1994b). The most Se-rich region of the SJV is the Panoche Creek alluvial fan which supports intensively irrigated land (Tidball et al., 1986; 1989). Salts and Se build-up on soils as a result of both the arid climate (i.e., less than 10 inches of precipitation and greater than 90 inches of evaporation) and poor drainage (i.e., clay layers impede downward movement of water causing water-logging of the root zone).

The SJV has a net negative annual water budget (evaporation exceeds precipitation). Prior to development of the water management system, a permanent shallow groundwater table only occurred in groundwater discharge zones near the SJV trough. The present shallow ground water and attendant subsurface drainage flows are mainly the result of water management including massive irrigation. Micro-management seemingly has enabled agricultural production to continue at a high rate without excessive abandonment of lands.

Massive irrigation leaches salt and Se and moves them into aquifers and surface waters. Installation of subsurface drains increases the speed, volume, and control of the drainage of shallow groundwater that impedes agricultural production. Collection of drainage from irrigated soils in drainage canals enables efficient discharge into surface waters. In 1960, both the federal government and the state of California committed to provide irrigation and subsequent drainage of irrigation wastewater for the Central Valley Project of the San Luis Unit of the western SJV (Public Law 86-488, 1960; California Burns-Porter Act, 1960). A history of legislation and planning since the inception of a master-drain is given in Table 1 and detailed in Appendix A. The San Luis Unit includes agricultural lands that total over 700,000 acres in the Westlands, Panoche, Broadview, Pacheco, and San Luis Water Districts of the Westlands and Grassland regions or subareas (USBR, 1981) (Figures 3 and 5). It was hoped that the increased water supply (to satisfy moisture demand by climate and crops) would be balanced by salt leaching and drainage, even though amounts of water required are on a massive scale (USBR, 1955; 1962; 1978; CDWR, 1979). Simple water and mass balance observations explain the attractiveness of an engineering solution that would increase salt and water discharge from the SJV.

Prediction of long-term reservoir: how sustainable is discharge?

In planning for the envisioned hydrologic balance, a distinction was made between managing the accumulated hydrologic imbalance (area of affected land) and managing the annual imbalance (rate of water table rise) (CH2M HILL, 1988; SJV Drainage Program, 1989). Short-term objectives would work toward hydrologic balance by stemming the rate of deterioration, while reclaiming existing "problem lands" would require releasing from storage a large accumulation of water and salt. Achieving hydrologic balance would not achieve salt balance. Salts would continue to accumulate in the soils and aquifers of the SJV. Planned volume of drainage discharge increased over the 100-year management period (USBR, 1978; 1983) (Appendix A, Table A1). Salt loads were calculated for a period of 50 years into the future, with a maximum release occurring after 40 years of discharge. Later estimates (USBR, 1983) also planned for 100 years of discharge to the SLD, with a slowing in the rate of increase after 40 years (Appendix A, Figure A3).

The geohydrologic balance of Se (or salt) ultimately determines the degree of contamination build-up in the SJV (Appendix A, Tables A2 and A3). The primary geologic inventory of Se in the Coast Ranges is the ultimate source of influx. Drainage from the SJV is the source of efflux, whether natural or artificially accelerated by engineering means. The internal reservoir of labile Se in SJV is growing because the rate of removal of Se-enriched salts from the valley is naturally slow. In general, calculations of the amounts of Se in the reservoir within the Panoche Creek alluvial fan also confirm the massive nature of Se accumulation in the SJV. Calculations based on two scenarios (Appendix A, Tables A2 and A3) show that no long-term reduction in Se discharge would be expected for 63 to 304 years at the lower range of reservoir projections, even if influx of Se from the Coast Ranges could be curtailed. Drainage of wastewaters outside of the SJV may slow the degradation of SJV resources, but drainage alone cannot alleviate the salt and Se buildup in the SJV, at least within a century, even if no further inputs of Se from the Coast Ranges occur. On a current, specific scale: 1) the Panoche Creek upper watershed Se load is a small percentage of the total annual load except during infrequent large magnitude storms (Presser et al., 1990; Appendix B, Table B8); and 2) in 1998 (a wet year), 16% of the Panoche Creek load was in the dissolved fraction and 84% was in the suspended fraction (Appendix A, Table A3; U.S. Geological Survey, 1999; Kratzer, et al., in press). Selenium concentrations in sediment samples, however, were relatively low historically and in 1998 (1-2 μg/g), depending on the large mass of sediment eroded during storms to accounts for the large loading of Se during runoff (Presser, et al., 1990; Presser, unpublished data). Dissolved Se in runoff samples ranged from 31 to 85 μg/L in monitored storms in WY 1998 (Appendix A, Table A3; U.S. Geological Survey, 1999; Kratzer, et al., in press).

<u>Selenium concentrations in source waters</u>

The effect of the large reservoir of Se calculated above can be seen in the quality of the ground water in the western SJV (Table 3). Extensive measurement and study of the groundwater aquifers in the SJV have been made since 1917, but Se concentration analyses were not a part of water quality studies until the 1980's (Mendenhall et al., 1916; Davis and Poland, 1957; Presser and Barnes, 1984; 1985; Deverel et al., 1984; SJV Drainage Program, 1989; 1990a). Average Se concentrations in drainage sumps in the area of the Panoche Creek alluvial fan range from 140 to 4,200 μg Se/L (Presser and Barnes, 1985). These concentrations are reflective of shallow groundwater conditions as opposed to managed drainage, which may be blended. Studies in 1989 in the area of the Panoche Creek alluvial fan showed Se concentrations ranged from 96 to 7,300 μg/L Se in individual sump discharges or well samples at depths up to 50 feet below land surface in areas served by subsurface drains (Gilliom et al., 1989) (Table 3). The Se concentrations depended, in part, on the number of years the fields were drained. The concentration of Se in subsurface drain water in the area of the wells ranged from 400 to 1,000 μg/L Se. A more recent compilation used in the evidentiary process (Wanger, 1994; Stevens and Bensing, 1994; WWD, 1996) and in regulatory planning shows concentrations in shallow groundwater range from 75 to 277 μg/L Se (range of means) (SJV Drainage Program, 1990a; CCVRWQCB, 1996c; d) (Table 3). Data presented in testimony and by the state (Table 3) project an average concentration of Se in shallow ground water and hence, subsurface drainage, of at least 150 μg/L Se in the farming areas affected by the Panoche Creek alluvial fan.

Most Se concentrations in shallow ground water listed in Table 3 are above those concentrations of blended discharges presently regulated as oil refinery effluents (50 μg/L Se) and above the concentration estimated that is possible with treatment (50 μg/L Se) (WWD, 1996). Most Se concentrations in currently regulated discharges to evaporation ponds in the southern SJV (Tulare and Kern subareas, Figures 3 and 5) are above those associated with avian risk, and consequently dischargers are required to provide mitigation and alternative habitat (CSWRCB, 1996c).

The effect of the large reservoir of Se on recent subsurface drainage flow and quality is generalized from data collected during frequent sampling of drainage source water (i.e. current agricultural discharges to the SJR in WY 1997 and 1998 from the Grassland subarea, see Appendix B, Tables B9 and B10; and Appendix D) (USBR et al., 1998; 1999). Selenium concentrations in drainage are not diluted when the volume of drainage increases, except in infrequent, extreme precipitation events (Figure 6). Generally, more input of water to western SJV soils results in more Se transport and increased Se load with increased hydraulic discharge. These observations from recently collected data confirm the effect of irrigation in creating increased Se loads from the SJV. When considering Se source waters as opposed to receiving waters, Se concentration in source waters will increase as more irrigation water is applied and more discharge occurs. Therefore, Se loads increase over those seen without irrigation. Testimony in the state water right hearing similarly confirm that the action of irrigation supply (mainly from the Central Valley Project) is the principal cause of the drainage discharge of salinity, and hence, the cause of violations of water quality objectives for salinity for the Bay-Delta (CSWRCB, 1999a).

Removal of salt (and Se) also is slowed by the recycling of the SJR (Figure 5). The SJR can be almost completely diverted back into the SJV before it enters the Bay-Delta. In the past, recycling has occurred during most months of the year and during all months of many years (USBR Central Valley Operations Office, Daily Delta Outflow Computation; EA Engineering, Science, and Technology, 1999). The recycled SJR water is then used again in irrigation. As noted above, the degree of recycling is determined by water management. Water management began changing toward less recycling in 1994 and direct throughput of the SJR may increase in the years ahead to help restore SJR fish and fish habitat. A reduction in recycling and an increase in drainage discharge during seasons of elevated flows are strategies for slowing the salinization of agricultural soils. However, management to meet all goals including meeting the salinity standard for the SJR at Vernalis is complex. Strategies may include the need for storage or holding ponds to optimize timed release of drainage and meet the salinity standards for the SJR at Vernalis. Agricultural drainage outputs are not, in general, coordinated with periods of high river flows (Appendix A, Figure A11).

Drainage management

Management plans have discussed "in-valley" and "out-of-valley" drainage management alternatives. "In-valley" solutions imply local storage and treatment of Se-rich drainage. Satisfactory treatment technologies have not yet been demonstrated and storage does not seem sustainable (SJV Drainage Program, 1990a). "Out-of-valley" solutions mean export of the salt-laden drainage (and its Se load) to somewhere else. The most frequently mentioned of these solutions is an extension of the SLD with discharge to the Bay-Delta.

Planning for a drain to carry salt-laden irrigation return water (and the accompanying Se) from the SJV began in 1955 (Table 1). An 85-mile section of the SLD was completed in 1975, to collect irrigation drainage water from one section of the valley, the WWD (i.e., Figures 3 and 5, Westlands subarea). The SLD began discharging concentrated drainage water in 1981 to Kesterson National Wildlife Refuge (Figures 3 and 5), a heavily populated bird sanctuary on the Pacific Flyway (USBR, 1986; Presser and Ohlendorf, 1987). The Kesterson National Wildlife Refuge ponds were used as terminal evaporation ponds until the remaining miles of the canal could be built. In 1983 deformed birds were discovered at Kesterson Reservoir, a reservoir consisting of twelve ponds, at the discharge point of the agricultural drainage. Subsequent monitoring revealed elevated levels of Se in the organisms within the ponds (Saiki and Lowe, 1987). Avian deformities were ultimately linked to Se exposure from food chain contamination (Ohlendorf et al., 1986; Presser and Ohlendorf, 1987). The SLD was ordered closed by the U.S. Department of Interior in 1985 and the low-lying parts of Kesterson National Wildlife Refuge were buried under 18 inches (46 centimeters) of imported topsoil in 1988 (USBR, 1986). Elevated Se concentrations persist in the remediated terrestrial ecosystem at Kesterson Reservoir (CH2M Hill, 1996; 1997; 1999a; 1999b; Presser and Piper, 1998).

Management of Se differed among regions (subareas) in the SJV in the 1990's. The five subareas (i.e., Northern, Grassland, Westlands, Tulare, and Kern) of the western SJV were designated based on hydrologic and geologic features and on options for management of irrigation and agricultural wastewater discharge (SJV Drainage Program, 1990a) (Figures 3 and 5). Selenium-laden wastewater is stored as ground water in some areas of the valley. In others, drainage is collected in privately owned evaporation ponds located on farms, although reproductive impacts, including teratogenesis (deformation of young) and death of avian offspring, were observed in some of these ponds and associated wetlands (Skorupa, 1998a). Some drainage is discharged into collector canals, sloughs, and wetlands that eventually discharge into the SJR. The Grassland Bypass Channel Project was implemented in 1995 [i.e., water year 1996 (WY 1996); a water year begins in October] to again begin to collect drainage from one area of problem lands and transport drainage via the SLD to outside the SJV. Drainage from the SLD is currently discharged into Mud Slough, a tributary of the SJR (Figures 3 and 5). The goal is to remove drainage inputs from wetland supply channels, a national wildlife refuge, and a state wildlife area by shifting drainage discharges further downstream into the SJR. Degradation is occurring in a smaller area of ecosystems while phased-in management activities potentially reduce loads from historic levels and thus attempt to comply with water quality standards (USBR, 1995; USBR et al., 1998; 1999).

<u>Forecasting loads of selenium: general consideratons</u>

The problem of progressive soil salinization and the build-up of ground water contamination could require collection of drainage from larger and larger areas of the SJV if agricultural activities continue and a drainage outlet is available. A realistic, long-term evaluation of the potential for Se discharge must fully consider both the present and the potential future extent of the problem (Appendix B).

Identification and classification of *problem lands* in the SJV took place as early as 1930 (Ogden, 1988). Since the 1950's, technical studies have estimated the extent of the acreage requiring drainage under varying conditions of water import, water export, salinity, and groundwater levels. In general, all of these early studies predicted a worsening fate if an out-of-valley drainage conveyance is not provided. For example, in 1955, developers of the CVP's San Luis Unit projected the *acreage affected* by salinity would increase from 12,000 acres in 1967 to 35,000 acres in 1976 (USBR, 1978; Gaines, 1988; Ogden, 1988; Prokopovich, 1989). The water purveyors thought *land requiring drainage* would increase from 96,000 acres in 1954 to 270,000 acres in 1967.

In more recent studies, the SJV Drainage Program conducted *"comprehensive studies to identify the magnitude and sources of the drainage problem, the toxic effects of selenium on wildlife, and what* *actions need to be taken to resolve these issues"* (SJV Drainage Program, 1989). Between 1985 and 1990, the joint federal/state program (SJV Drainage Program, 1990a) predicted areas of *problem acreage* (land characterized by water-logging and related water quality problems) and volumes of *problem water* (the annual drainage water volume that must be managed because of adverse impacts to agriculture or aquatic resources) (Appendix B). The program developed an "in-valley" management plan for agricultural subsurface drainage with specific management alternatives (SJV Drainage Program, 1989; 1990a). The goal was to make progress both in managing and treating drainage-water toxicants and developing long-term solutions to address the elevated groundwater conditions and the annual salt build-up that eventually limit the uses of valley lands and ground water. The SJV Drainage Program's regional studies and data provide much of the information used in our assessment of loads from the subareas of the SJV (Appendix B). The benefits expected, during the 50-year management period, included continued agricultural production at present levels without predicted abandonment of lands due to salinization; and restoration/protection of fish and wildlife resources from the adverse effects of Se in receiving waters. Recommended monitoring based on the developed regional framework, if implemented, would add site-specific data and analysis necessary for long-term success of the SJV Drainage Program. Recommendations for treatment techniques were not included because success of technology on a large-scale was not proven as of 1990 (SJV Drainage Program, 1990a). Implementation of the management plan was only partial and systematic monitoring and data analysis has not occurred (SJV Drainage Implementation Program, 1998).

The SJV Drainage Program management plan (1990a) estimated a *problem area* of 444,000 acres would create 314,000 acre-feet (AF) of *problem water* annually by the year 2000. The *problem area* would increase to 951,000 acres with an increase in *problem water* to 666,000 acre-feet by year 2040. For these estimates of acreage, the SJV Drainage Program used a *criterion of sufficiently elevated salinity and boron concentrations in ground water* to limit use of the water and affect crop selection (i.e., lands with an actual drainage problem). The SJV Drainage Program also estimated acreage with a potential drainage problem using a *criterion of an area with a shallow ground water within 0 to 5 feet of land surface*. Using this criterion, estimates ranges from 765,000 acres in 1990, to 918,000 acres in year 2000, to 1,057,000 acres in year 2040. Using the *criterion of lands contributing the largest percentage of selenium to drainage discharge (i.e., lands overlying areas of shallow ground water with selenium concentrations of greater than 50 μg/L)*, 264,000 acres were projected as affected in 1990. It was estimated that 84,000 acres of land would have to be abandoned by 2000 and 460,000 acres by

2040 if the SJV Drainage Program management plan was not implemented. Land retirement recommended by the SJV Drainage Program by 2000 was 21,000 acres and by 2040, 75,000 acres.

Further documentation provided in 1992 for the San Luis Unit Drainage Program simply stated that all the major USBR and interagency studies (Table 1, 1955; 1962; 1964; 1972; 1979; 1984; and 1990) found similar magnitudes of the drainage problem (USBR, 1992). As noted in recent testimony given in state water right hearings, the total acreage of lands impacted by rising water tables and increasing salinity is approximately 1,000,000 acres in the SJV (CSWRCB, 1999a). A recently instituted land retirement program has identified willing sellers of up to 15,000 acres in the Westlands and Tulare subareas and has acquired several hundred acres as of 1998 (U.S. Department of the Interior, 1999; SJV Drainage Implementation Program, 1999b).

How to determine load

One approach to forecasting Se loads is to examine historic records and planning efforts for agricultural discharges with the goal of developing relations between acreage, drainage generated or discharged, Se concentration, and load of Se. Forecasts in this report were based on historical, annualized drainage volumes and assigned concentrations because these are the data and tools available (Appendix B). Recent monitoring programs have failed to collect the data necessary to develop cause and effect relations, for example, between Se distribution and concentration in ground and surface water and implementation of management actions. The limitations of the available record are significant (Appendices C and D and see discussion of each subarea); nevertheless, broad estimates are feasible.

Management of Se loads involves three factors (SJV Drainage Program, 1990a):

- *Acreage requiring drainage*. Acreage is expressed as either the extent of *problem acres* or tile-drained acres. *Problem acres* generate a generic *problem water* as an expression of the extent of affected acres. In our context, tile-drained or subsurface drained acres would be expected to generate concentrated drainage as opposed to *problem water*. Neither categorization adequately addresses the regional pooling of drainage to include *upslope* components. In our analysis, the distinction made between *problem water* and subsurface drainage helps in forecasting future loads by enabling an assignment of water quality based on this distinction.
- *The volume of drainage generated per acre*. A factor is applied (acre-feet per acre) to the amount of affected acreage (acres) to estimate the amount of drainage generated (acre-feet).

The average annual volume of *problem water* generated from *problem lands* under conditions in 1990 was estimated as 0.7 acre-feet per acre per year (SJV Drainage Program, 1990a). The SJV Drainage Program predicted that changes in on-farm drainage management practices could reduce the volume generated to approximately 0.4 acre-feet per acre per year. Recent updates of conditions in the Grassland subarea show an average annual volume per acre of 0.38 to 0.47 acre-feet per year (Appendix B, Table B8). An average annual *pollution abatement objective* of 0.2 acre-feet per acre per year has been considered as necessary to meet Se load limits in the Grassland subarea (Environmental Defense Fund, 1994).

- *The concentration of Se in the irrigation drainage*. Reconnaissance-level data on Se concentrations in shallow ground waters are available from all areas (Table 3) (Deverel et al., 1984; SJV Drainage Program, 1989; 1990a). The concentration of Se in effluent drainage reflects a managed balance of input, output, and storage. Treatment technologies (mostly unspecified) or dilution with Se-poor water (blending) can be used to reduce concentrations below those found in shallow ground water. Most technical evaluations have not applied concentrations to estimates of drainage volumes to calculate potential loads of Se (e.g., SJV Drainage Program, 1990a).

All three factors can vary greatly depending upon assumptions about management strategies. Two possible alternative management futures were defined by SJV Drainage Program: 1) no implementation of the SJV Drainage Program management plan, 0.60 to 0.75 acre-feet per acre per year generated drainage, namely, "*without future*" and 2) with implementation of the SJV Drainage Program management plan, 0.40 acre-feet per acre per year generated drainage, namely, "*with future*" (SJV Drainage Program 1989 and 1990a). A third condition defined for use in our projections is called "*with targeted future*". The "*targeted future*" condition applies a factor of 0.20 acre-feet per acre per year of generated drainage, exemplifying the lowest, although probably not realistic, irrigation water return. The "*without future*" alternative, in which the management plan is not implemented, result in less volume of drainage because of the predicted abandonment of approximately 84,000 acres of land due to salinization by the year 2000 (Appendix B, Tables B11 through B17). If the SJV Drainage Program plan were implemented, the amount of drainage would be reduced to 0.4 acre-feet per acre per year, but the total land in production would be preserved.

We employ a mixture of metric and English units in the forecasts and the following discussion. This is unconventional for a scientific report, but is done here to aid communicating our study to the widest audience in the most recognizable terms. The agricultural discharges of Se are expressed as loads of Se in pounds (lbs); area is described in acres and volume of discharge is expressed in acre-feet (AF) or million acre-feet (MAF); Se concentrations are expressed as μg Se/L (equivalent to the regulatory term ppb), or μg Se/g (equivalent to the regulatory term ppm). Conversion between these units and scientific units, which are used in the analysis of Se ecological effects, can be found in Table 4. Selenium load (in pounds) is calculated using the equation:

[Se concentration (μg Se/L or ppb) X volume of drainage (acre-feet)] X 0.00272 = load of Se (lbs),

or

[Se concentration (μg/L) X [(acres) X (acre-feet per acre)] X 0.00272 = load of Se (lbs),

where 0.00272 lbs Se per acre-foot is equal to a concentration of one part per billion (μg/L) Se in an acre-foot of water.

Characteristics of agricultural subareas

The links between demands for drainage and estimates of potential loadings of Se require consideration of specific agricultural subareas in the SJV (i.e., Northern, Grassland, Westland, Tulare, and Kern subareas, Figures 3, 5 and Appendix B). Evaluation of issues requires understanding the history, agricultural activity, and geohydrologic characteristics of these subareas. A brief summary is given below for each subarea designated by the SJV Drainage Program (1989 and 1990a). Data given in bold in parentheses is from the SJV Drainage Program (1989).

- *Westlands Water District (WWD) and Subarea (770,000 total acres; 576,000 irrigated acres; 5,000 acres with subsurface drains, relieving salinization in 42,000 acres).*

The Westland subarea (Figures 3 and 5) was the first to discharge irrigation drainage to the SLD, as noted above. This drainage was released into Kesterson National Wildlife Refuge from 1981 to 1986. As a result of the ecological crisis associated with the Kesterson National Wildlife Refuge, Westlands subarea now has a "no discharge" policy. Drainage is recycled onto farmlands and/or "stored" in the underlying groundwater aquifers, where irrigation and aquifer supplies are used for dilution. Currently, as a result of a U.S. Court of Appeals decision (Hug et al., 2000), the USBR is ordered to initiate the process to provide drainage service to the San Luis Unit. The specifics of such drainage service have not been provided.

The data record from the Westland subarea is particularly limited with no specific monitoring for Se since closure of the SLD in 1986. Only data on groundwater elevations are available in the area most impacted by geologic sources of Se (WWD, 1998). This area is potentially the greatest generator of Se load in the SJV because it, more than any other subarea, encompasses the Panoche Creek alluvial fan area (Presser et al., 1990). This fan and interfan area receive the most seleniferous runoff and erosion from the Coast Ranges (Tidball et al., 1986; 1989; Presser, 1994b). Used here are the estimates of areas of shallow groundwater that impact farming presented in management plans, testimony, and a recent status report by WWD (1996; 1998). Westlands Water District contended (CSWRCB, 1985) that the 5,000 drained acres actually represented drainage from 42,000 acres because of the downslope location of the drainage collection system.

Historic management plans predicted 170,000 acres of the WWD would be affected by salinization by the year 2000 and 227,000 acres would be affected by 2040. It is estimated that immediate drainage needs exist for 200,000 acres, resulting in 60,000 acre-feet of drainage per year (e.g., 200,000 acres X 0.3 acre-feet per acre = 60,000 acre-feet) (USBR, 1992; WWD, 1996) (Appendix B, Table B2). No formal long-term stipulations control the ultimate fate of the drainage water in the WWD, but pressure to discharge Westlands subarea drainage into a completed SLD extension to the Bay-Delta is increasing as lands become waterlogged, the quality of the soils declines, and ground water quality declines.

Because discharges from the Westlands subarea were discontinued in 1986, no current direct measurements of effluent quality are available. Historic discharges provide some guidance. Average Se concentrations that were discharged to Kesterson National Wildlife Refuge from the historic SLD ranged from 330-430 μg/L Se in 1983 and 1984 (CSWRCB, 1985; Presser and Barnes, 1984; 1985) and as quoted from regulatory documents, from 230-350 μg Se/L (Table 3) (WWD, 1996). This resulted in 4,776 lbs per year of Se discharge and a discharge of 17,400 lbs to Kesterson Reservoir over the period of discharge (USBR, 1986) (Appendix B, Table B1). We will term a cumulative 17,400 lbs load of Se as 1 kesterson (kst). The use of this unit provides perspective on the quantity of Se that was a hazard to wildlife when released directly to a wetland (Presser and Piper, 1998).

Testimony in recent legal proceedings summarized the data for Se in broader areas of shallow ground water in the WWD (Table 3). Mean concentrations ranged from 163 μg/L to 300 μg/L in different studies. The USBR suggested the most likely estimate of average Se concentration in shallow ground water is 150 μg/L. With treatment or blending, management plans asserted that concentrations could be reduced to as low as 50 μg/L.

- *Grassland Subarea (707,000 total acres; 311,000-329,000 irrigated acres; 51,000 drained acres).*

The Grassland subarea is the second subarea requiring drainage included in the original agreement to provide drainage service (see San Luis Unit, Delta-Mendota Service Area, Table 1). This area of the western SJV is to the north and downslope of the WWD (Figure 3; SJV Drainage Program, 1990a). The Grassland subarea contains 70,000 to 100,000 acres of land that have historically contributed the majority of subsurface drainage to the SJR (Appendix B, Table B3). The adjacent Grassland federal, state, and private riparian wetlands contain the largest tract of habitat remaining in the SJV. Varying lengths of the complex channel system within the wetlands have been and are currently utilized to convey agricultural drainage to the SJR. Mud and Salt Sloughs (Figures 3 and 5) are examples of tributaries that flow through the wetlands of the Grassland Resource Conservation District and the San Luis National Wildlife Refuge Complex. In 1995, the discharge from approximately 100,000 acres of farmland was consolidated into a 28-mile segment of the original SLD (renamed the Grassland Bypass Channel Project) in order to reduce contaminated wetland water supplies, but the inputs to the SJR remain unchanged (USBR, 1995).

The available historical record from the Grassland subarea includes data from discharges to the SJR that were collected mainly to compare Se concentrations in the river to water quality objectives (Table 5; Appendix B, Tables B4 to B7; and Appendix C, Figure C1). Only recently have measurements or estimates of flow been conducted consistently, so limited data exists to determine Se loads (USBR et al., 1998; 1999). Historic data from the CCVRWQCB that document Se and salt loading to the SJR were recently reviewed (CCVRWQCB, 1998f). Limitations were described in measuring flow and concentration and in the methodology used to calculate loads and regulatory targets.

The effects of Se discharges on water quality are monitored for the SJR at Crows Landing (below Mud and Salt Sloughs and downstream of the Merced River), Patterson**,** and Vernalis (Figures 3 and 5), where the SJR enters the Delta (Table 5). The monitoring shows that:

- The load of Se is variable from year-to-year from 1986 to 1998. Loads vary at the upstream source from 5,083 to 11,875 lbs per year among years; at Crow's Landing they vary from 3,064 to 14,291 lbs per year (Table 5).
- The variability in load is at least partly driven by precipitation, with larger loads in wet years than in dry years (Appendix A, Figures A9 and A10).

- Estimated Se loads in the source waters (i.e., agricultural drains or canals) differ from load estimates for the SJR monitoring sites. Some downstream estimates are higher and some are lower than the drainage source estimates. The difference among sites is usually small compared to the year-to-year variability in the initial load except for unusually wet years (e.g., 1995 and 1998). Reductions in downstream loads may occur because of uptake by sediment and biota (Presser and Piper, 1998).
- Besides biochemical reactions, some of the variability among sites undoubtedly occurs because the monitoring data have important deficiencies (Presser and Piper, 1998). As of 1999, the monitoring did not include determinations of particulate Se, Se speciation, Se in sediments, or sufficiently frequent analyses to accurately depict loading during variable flows. Discharge schemes that involve regulating concentrations or loads in the SJR will require more reliable monitoring.

Despite some deficiencies, Se concentrations in the drainage from the Grassland subarea are better documented than in other subareas. Monthly average total Se concentrations in blended drainage ranged from 40 to 105 µg Se/L in 1997 and 1998 (USBR et al., 1998; 1999) (Appendix B, Tables B9 and B10). The daily range was 15 to 128 µg Se/L over this period (Appendix D, Figures D15 and D16). The annual average Se concentration observed in collected drainage from the Grassland area was 62 µg/L in WY 1997 and 67 µg/L in WY 1998 (Table 5 and Appendix A, Tables B9 and B10) (USBR et al., 1998; 1999). These averages are comparable to the historical average of 64 µg/L from 1986 to 1994 (Table 3) (CCVRWQCB, 1998 d; e; f; g; h). Modeled discharges from the Grassland subarea have estimated 80 to 150 µg/L Se (Table 3) (SJV Drainage Program, 1990a; CCVRWQCB, 1996a; b).

- *Tulare subarea (883,000 total acres; 506,000-551,000 irrigated acres; 42,000 drained acres) and Kern Subarea (1,210,000 total acres; 686,000 irrigated acres; 11,000 drained acres)*

Tulare and Kern subareas are located in the southern SJV and discharge to privately owned evaporation ponds. Sixteen ponds (5,900 acres) were initially developed from approximately 1975 to 1990 in the Tulare subarea and ponds covered 1,300 acres of ponds in the Kern subarea (SJV Drainage Program, 1989). Since that time, no new ponds have been built and many ponds have been closed, CCVRWQCB, 1997; 1998c) (Appendix B, Tables B19 to B21). The subareas are internally drained basins with relict lakebeds (i.e., Tulare, Goose, Buena Vista, and Kern) as dominant geologic features.

The lakebeds are little influenced by the Panoche Creek alluvial fan but are surrounded by geologic sources of trace elements from both the Coast Ranges and Sierra Nevada. Water quality is characterized by elevated concentrations of Se, uranium, arsenic, molybdenum, and boron (Fujii and Swain, 1995). The geochemistry is controlled in part by oxidizing and reducing zones in the lakebeds and surrounding alluvial fan and basin zones. Geomorphological features affect the placement and number of subsurface drains installed in the subareas. Delineated water quality zones affect the chemical composition of the discharge to specific evaporation ponds. Currently, subsurface drains are mainly limited to lower elevations of the lakebeds (42,000 acres in Tulare subarea and 11,000 acres in Kern subarea) (SJV Drainage Program, 1989).

Current estimates of acreage adversely affected by shallow ground water are “gross estimates” due to sparse data and extrapolation over a 696,000-acre study-area selected for coverage by the CDWR (1997). The study area boundaries differ from those given above as part of the SJV Drainage program designation. The CDWR has historically studied an area called the Tulare Lake region. Estimates based on data collected by the CDWR after 1991 are considered of some worth and could be used in future comparisons, but historic baseline values are suspect. The current disposition of ground water within 0 to 15 feet is unclear from the reported CDWR “gross estimates”. Initial estimates made by the SJV Drainage Program (1989) show the Tulare subarea with 320,000 acres of land with ground-water levels within 5 feet of land surface. Estimates for the Kern subarea show 64,000 acres are affected. For year 2000, the SJV Drainage Program estimates of affected acres increase to 366,000 in Tulare and 100,000 acres in Kern subarea.

The Se monitoring in Tulare and Kern subareas is limited to annual reporting by dischargers as required by the state as part of permit requirements for discharges to privately owned evaporation ponds (CCVRWQCB, 1993; 1997; 1998c; CSWRCB, 1996a; CCVRWQCB, Anthony Toto, personal communication, 1998) (Appendix B, Tables B19 to B21). Any discharges to evaporation ponds must be considered in estimates of valley-wide Se loads, although it is not clear, in view of the impacts to waterfowl populations (Skorupa, 1998a), whether these discharges will continue. Discharge from the Tulare subarea to private evaporation ponds is remarkable for being low in Se concentration when compared to the Se concentration in discharge from Westlands or Grassland subareas. The record is limited, but values measured in 1988, 1989 and 1993 through 1997 show most concentrations were below 10 μg/L Se, with the exception being the South Tulare Lake Drainage District discharge of up to 30 μg/L Se. Some higher Se concentrations, ranging up to 760 μg/L Se, have been reported in some discharges to smaller ponds (Table 3 and Appendix B, Tables B19 to B21). For the Kern subarea, limited data on inflows to evaporation ponds in 1988, 1989 and 1993 to 1997 show Se concentrations range from 83 to 671 μg/L, with the exception being the Lost Hills Ranch discharge of approximately 2 μg/L (CCVRWQCB, 1990 a and b). In general, Se concentrations in discharges from the Tulare subarea are less than 50 μg/L and for the Kern subarea are greater than 180 μg/L.

- *Northern subarea (236,000 total acres; 157,000 irrigated acres; 26,000 drained acres).*

The Northern subarea has been included here and in our forecasts for consistency with other regional evaluations. The Northern subarea presently drains to the SJR through both discharge and groundwater seepage. Estimates of acres demanding drainage have not been updated since 1990, nor are current records concerning Se available for compilation from this subarea. Most estimates suggest that drainage needs are relatively small compared to other areas (CH2M HILL, 1988; SJV Drainage Program, 1990a) and will remain so if access to the SJR for drainage remains available to the same degree (i.e., the subarea remains in hydrologic balance).

Development of forecasts

While most technical evaluations stop with estimates of *problem acreage* and *problem water* volumes, understanding the range of possible Se concentrations in drainage is critical to evaluating potential loads. To bracket possible Se concentrations in our different scenarios of Se loads from the western SJV, we will employ three concentrations in conjunction with different estimates of problem drainage volume and acreage (Appendix B). In general, a concentration of 50 μg/L Se in drainage is considered potentially available with *treatment*. Testimony in court hearings have centered around the fact that a non-specified treatment could lower the Se concentration to an overall 50 μg/L; then this product water would be disposed of in an extension of the SLD. Therefore, one scenario is that such treatment options will be available, and/or mixtures of drainage water will resemble those presently being released from the Grassland subarea (i.e., 62 to 66 μg/L Se). For this forecast we will use Se concentrations of 50 μg/L Se for treated or blended (i.e. diluted) drainage. Alternatively, another set of forecasts will assume a maximum case (300 μg/L Se), and one will assume the intermediate possibility [150 μg/L Se, an average for present day subsurface drainage waters in the Grassland subarea (CCVRWQCB, 1996c), near the mean (163 μg/L Se) presented for the 42,000 acres in WWD (Stevens and Bensing, 1994), and a conservative estimate (at least 150 μg/L Se) in WWD by USBR (Wanger, 1994)]. Given the quality of the ground water noted in our previous analysis of reservoir conditions (Table 3) and the lack of adequate monitoring to trace groundwater movement and Se concentrations as a function of time, these estimates may be conservative.

One further approach to forecasting potential total Se loads from the SJV and thus narrow the range of forecasts is to generate forecasts using a compilation of data on Se concentration and load that has become available from each subarea since the SJV Drainage Program (i.e., 1985 to 1990) (Appendix B, Tables B9, B10 and B19 to B21). It is recognized that this involves use of data which all have significant limitations. However, we stress the importance of collecting high quality hydro- and bio-geo-chemical data in the future. Nevertheless, the existing area-specific data incorporates the geographical heterogeneity of drainage in establishing the boundaries of potential Se discharges. This approach is not as broad as that of the SJV Drainage Program in that an extensive database documenting the implementation of management actions and their effects is not available as part of public record. But, the scenarios may be more reflective of specific geologic and hydrologic conditions in each of the five subareas.

Forecasting selenium loadings using the sum of data from all subareas

The total out-of-valley drainage is the sum from all five subareas (Figures 3 and 5) (Table 6). Table 6 is specific to SJV Drainage Program management option (implementation, i.e., "*with future*", no implementation, i.e., "*without future*", and "*with targeted future*") and projected year (1990, year 2000, year 2040) and gives ranges of combined annual Se loads potentially discharged from all five subareas. A wide range of Se loadings in the future from the western SJV is possible given the ranges of acre-feet of drainage and drainage quality. These scenarios based on the broad SJV Drainage Program approach do consider, to some extent, addressing the longer-term problem of an accumulated imbalance of water, salt, and Se and the sustainability of agriculture in the SJV, rather than just managing an annual imbalance.

One alternative is that the volume of drainage water will not increase beyond the volume of subsurface drainage that existed in 1990. If 100,000 acre-feet volume of subsurface drainage is discharged at an assigned concentration of 50 μg/L Se, then 3,600 lbs Se per year are projected. Assigned Se concentrations of 150 μg/L or 300 μg/L would yield loads of 40,800 or 81,600 lbs Se per year, respectively.

Total drainage can be projected using *problem acreage* across all subareas of the SJV (Table 6). Specifically, a forecast using an assigned concentration of 50 μg/L Se to represent blended generic drainage in conjunction with the most quoted estimate from the SJV Drainage Program of 314,000 acre-feet of *problem water* (i.e., year 2000 without implementation of the specified management plan) yields a load of 42,704 lbs Se per year. For year 2040, the amount of *problem water* would increase to 666,000 acre-feet, generating a load of 90,576 lbs Se per year at an assigned concentration of 50 μg/L Se.

A forecast using an assigned concentration of 150 μg/L Se to represent generic subsurface drainage and the SJV Drainage Program estimate of subsurface drainage of 144,000 acre-feet ("*with future*") in year 2000 yields a load of 58,751 lbs Se per year. For year 2040 under the condition of implementation of the SJV Drainage Program (303,600 acre-feet per year), the discharged load would be 41,290 lbs Se per year.

Using an assigned concentration of 300 μg/L Se in year 2000 and the least amount of estimated drainage (72,000 acre-feet per year "*with targeted future*"), the load discharged would be 58,753 lbs Se per year. In year 2000, 163,000 acre-feet (*without future*) at 150 μg/L Se would produce a load of 66,504 lbs Se per year. In year 2040, 223,000 acre-feet (*without future*) at 150 μg/L Se would produce a load of 90,984 lbs Se per year.

Forecasting selenium loadings using data from individual subareas

Using the same approach as above, specific loadings can be projected from each of the five subareas based on the detailed data given by the SJV Drainage Program for year 2000 and assigned concentrations of 50, 150, and 300 μg/L Se (Appendix B, Table B18). Appendix B (Figure B2a, b, c) illustrates use of a graphical tool to enable a prediction or projection of an annual Se load for any of the three assigned concentrations given a specific drainage volume. Again, the ranges are due to varying estimates of predicted *problem water* and subsurface drainage under different management alternatives.

In an effort to reduce the magnitude of the ranges given for each subarea, Table 7 gives the derivation and details of specific loads projected from each of the five subareas based on our compilation of currently available data on *problem acreage*, drainage volume, and Se concentration (Appendix B, Tables B9, B10 and B19 to B21). The values based on current data show only that amount discharged on the surface (e.g., to the SJR or to the evaporation ponds of Tulare and Kern subareas), and hence address only the present discharge being used to manage an annual imbalance of water, salt, or Se (Table 7). Depending on the type of data available from each subarea, projections were made concerning concentration or load. Because of the limited data and broad range of management alternatives across the subareas, maximum and minimum Se concentrations are given to bracket possible load scenarios at each specific volume of drainage. The projected concentration range is 5 to 10 µg/L Se for the Northern subarea , 68 to 152 µg/L Se for Grassland subarea, 49 to 150 µg/L Se for Westlands subarea (note, no current data, only testimony on acreage is available), 1.7 to 9.8 µg/L Se for Tulare subarea, and 175 to 254 µg/L Se for Kern subarea. Current conditions for each subarea (Table 6) give projected ranges for annual Se loadings of:

- Northern subarea 350 to 700 lbs Se per year
- Grassland subarea 6,960 to 15,500 lbs Se per year
- Westlands subarea 8,000 to 24,480 lbs Se per year
- Tulare subarea 91 to 519 lbs Se per year
- Kern subarea 1,089 to 1,586 lbs Se per year
    - Northern + Grassland + Westlands + Tulare + Kern subareas
      TOTAL 16,490-42,785 lbs per year

A graphical depiction of these projections for each subarea is given in Appendix B (Figures B4a through B4f). The high range and the low range of possible annual discharges are illustrated in Figures 7 and 8. As noted above, the largest Se loads come from Westlands subarea and Grassland subarea because of their combination of high *problem acreage*, and thus *problem water* volume, and high Se concentration.

Loading scenarios

Table 8 illustrates the total Se load from various combinations of subareas that might be included in a drainage collection system. These projected loads of Se provide the basis for determining the upper and lower limits of Se discharge from the western SJV that can be expected to enter the Bay-Delta via either a proposed direct conveyance to the Bay-Delta or the SJR. Secondarily, the projections provide the basis for determining the magnitude of Se load reduction that may become necessary to achieve a specific load of Se. Estimates like those in Table 8 implicitly assume that Se loads will be primarily driven by the demand for drainage, with different degrees of management superimposed. Of course, different demand scenarios than those shown are also possible.

The first four scenarios in Table 8 show that the load of Se increases from a minimum of 6,960 lbs per year to 42,785 lbs per year as additional area is added to drainage collection and/or as drainage volume and quality is less managed. The scenarios are:

- Only the existing discharges to the SLD from the Grassland subarea would be carried to the Bay-Delta. It seems unlikely that demand would remain at this level once an out-of-valley conveyance was available. Growing acreages of saline soils, rising ground water tables, and the availability of a conveyance facility are very likely to generate strong pressures from other areas to use the facility.
- Discharge from the Grassland subarea via the SLD or SJR would be discontinued and only the Westlands subarea would use an extension of the SLD.
- Grassland subarea discharges and Westlands subarea discharges would both be carried to the Bay-Delta; this seems a likely outcome if a conveyance is constructed.
- Drainage is collected valley-wide from all five subareas. This would require extensions of the SLD into Kern and Tulare.

A future that considered only agricultural needs might call for draining all 444,000 acres of problem lands. The fifth and sixth scenarios in Table 8 provide estimates of Se loads for a valley-wide drain that includes all potential problem lands estimated for the year 2000. The first of these calculations shows the range of Se loads expected if drainage management follows the plan submitted by the SJV Valley Drainage Program. If both quality (treating drainage to 50 μg/L) and quantity (e.g. reducing acre-feet per acre per year of drainage from 0.7 to 0.4) are managed, loads would calculate at 19,584 lbs per year. If only quality is managed, total Se loadings for the problem lands would then be 42,704 lbs per year. It is also possible that no management would be employed or management becomes less and less feasible. Drainage volumes in this scenario are not controlled and the quality of drainage deteriorates to 150 μg/L. In this case, Se loads would rise from a minimum in the range of 42,704 lbs per year to as much as 128,112 lbs per year (all problem lands, 0.7 acre-feet per acre per year, and 150 μg/L Se drainage).

As a comparison, the final forecast in Table 8 lists the load targets set in recent management plans for discharge to the SJR from the Grassland subarea (USBR, 1995; CCVRWQCB, 1998a). The target Se loads range from 1,394 lbs per year to 6,547 lbs per year depending on flow (i.e., wet or dry year).

Scenarios based on the capacity of an extension of the San Luis Drain

It is also feasible that exports of Se from the SJV could be determined by assigning a water quality goal to the drainage in a SLD extension and operating the drain at some pre-defined capacity (Table 9). The drain is presently designed to flow at 300 cubic feet per second (cfs) or carry approximately 220,000 acre-feet per year. That capacity could be a factor limiting loads, if a water quality standard is employed. Forecasts are given for 1) 50 μg/L representing an overall average given in testimony that treatment technologies (so far unspecified) or blending could achieve and near present day discharge from Grassland to the SJR (i.e., 62-67 μg/L; 2); 150 μg/L Se representing an average for current subsurface drainage without blending in the Grassland subarea (CCVRWQCB, 1996c) and near the mean (163 μg/L) presented for shallow groundwater from 42,000 acres in the Westlands subarea (Wanger, 1994); and 3) 300 μg/L representing a concentration approaching that discharged from WWD to Kesterson Reservoir from 1981 to 1985. It is notable (and probably a function of the original drain design, USBR, 1978; Brown and Caldwell, 1986) that the range of loadings derived from the 50 to 67 μg/L quality forecast and that from a drain managed at full capacity is 30,000 - 40,000 lbs (Table 9), are within the probable forecast derived from drain demand to manage the current annual imbalance from specific subareas in Table 8. If the drainage conveyance discharges 150 μg/L Se, at full capacity, the loading forecast converges on that estimated from all problem lands with little management (Table 9).

Despite the range of assumptions and range of possible outcomes considered in Tables 8 and 9, there is some convergence of the forecasts, irrespective of how they are derived. Load targets result in the smallest and most easily managed Se inputs to the Bay-Delta. Selenium loads based upon the demand for drainage converge on a mass discharge of 15,000 to 45,000 lbs of Se per year, if volumes and concentrations are carefully managed. Loads quickly grow beyond this level, if more land is drained and/or volumes or drainage quality are poorly managed or controlled.

The San Joaquin River as a conveyance facility, a de facto drain

The above estimates present Se loads primarily defined by demand from agriculture, and collection in an extension of the SLD. An alternative is to assume that water quality in the SJR would determine Se discharges, and no drain would be constructed. Two approaches have been discussed historically. Both approaches consider only the amount of dilution water available; no consideration is given to defining the assimilative capacity of the receiving water (i.e., the SJR) based on the bioaccumulative nature of Se.

1. *Total Maximum Daily Load or Total Maximum Monthly Load models*. This alternative models load allocations based on historical flows in the SJR. A water quality standard is applied to design flows to calculate a Se load limit for dischargers (Environmental Defense Fund, 1994). This is the technique mandated by USEPA for discharges to impaired water bodies such as the SJR (Clean Water Act, as amended, 1987; USEPA, 2000). The SJR compliance site for the 130-miles of impairment is the SJR at Crows Landing. This site is below the confluence with the Merced River, but above the SJR at Vernalis that is considered the entrance to the Bay-Delta (Figure 5). Between the Merced River confluence and Vernalis, the Tuolumne and Stanislaus Rivers flow into the SJR. Inherent in the TMDL model approach are an identification of sources and a program of load reduction to achieve compliance with water quality objectives.
2. *Real-time model*. This alternative goes one step further than TMDL modeling in that discharges are allocated based on real-time updates of flow (i.e., instantaneous measurements). This means maintaining a constant Se concentration at or below the water quality criterion (5 μg/L, the USEPA criterion is one suggestion) by varying load with flow (Karkoski, 1996). (Note: If real-time discharge were instituted, salinity measurements would need to act as a surrogate for Se measurements, since technology is not available to assess Se on a real-time basis). Loads based on real-time dilution maximize disposal of Se by adjusting the timing of discharges to coincide with dilution capacity of the river. Large loads may be released in months of high flow during the winter and spring. Holding ponds may be necessary for storage of drainage during low flow seasons in the SJR to avoid violations of water quality objectives. This methodology provides no certainty for the amount discharged per month or per year nor does it provide a means to assess long-term progress toward load reduction for impaired water-bodies.

As such, it is of less value that the TMDL approach in regulating the SJR as a Se-source water for the Bay-Delta.

Appendix C details the historical record used for derivation of loads for the SJR at Crows Landing and the load allocations for the dischargers using the TMDL, TMML, and real-time models. These models encompass both quasi-static and dynamic modeling of flows. The quasi-static TMDL and TMDL derived loads range from 1,394 to 6,547 lbs Se per year. Initial estimates for the dynamic real time model suggested loads would vary from 2,605 to 17,605 lbs per year (Karkoski, 1996) depending upon flow regimes.

Our estimates of Se loads conveyed by the SJR to the Bay-Delta treats the SJR as a Se source water for the Bay-Delta using an annual static inflow for the SJR at Vernalis based on wet or dry year flows and consideration of recycling. The main consideration in our development of this type of scenario in which the SJR is used as a *de facto* drain from the SJV is that the starting point is the targeted load. This is a supply driven strategy, with consideration of environmental protection a priority, rather than a load driven by agricultural demand. The effects on the SJR itself, of managing the constant concentrations in view of bioaccumulation are not known and are not considered here.

To obtain these modeled loads we used several assumptions about flow conditions (Table 9):

- little recycling of the SJR occurs in a wet year therefore 3.0 MAF enters the Bay-Delta annually
- 1.1 MAF of SJR inflow is allowed to enter the Bay-Delta annually indicative of partial SJR inflows in a wet year or total SJR inflow in a dry year.
- almost complete SJR recycling is 220,000 AF comparable to the capacity of the existing SLD

A range of 60 to 2,992 lbs Se would actually reach the Bay-Delta under the latter condition (probably like the drought years between 1987 through 1994) (Table 9). Maintaining a criterion of 5 µg Se/L in the SJR allows a load of 14,960 lbs per year to 40,800 lbs Se per year to enter the Bay-Delta at the two higher hydraulic discharges. Maintaining the USFWS proposed criterion of 2 µg Se/L would result in a range of 5,980 to 16,320 lbs Se per year.

Summary

Even though the full range of possible Se loadings to the Bay-Delta from the western San Joaquin Valley is large, current proposals, management plans, and history narrow the possibilities into three groups, depending upon management strategy:

- *Supply-driven management (3,000 to 8,000 lbs Se per year)*: By this we mean management that puts priority on environmental protection and targets a load that cannot be exceeded. For example, the TMDL/TMML approach target loads for the SJR from Grassland subarea alone of 1,400 to 6,500 lbs annually to stay below the 5 μg/L Se criterion depending upon flow regime for the SJR. The present prohibition for discharge from the Grassland subarea or drainage basin targets a load of 8,000 lbs.
- *Demand-driven load with management of land and/or drainage quality (15,000 to 45,000 lbs Se per year)*: By this we mean Se loads are driven by the agricultural demands for draining saline or waterlogged soils. We assume the quality and quantity of the drainage are controlled by managing volume per acre and/or quality of the drainage. For example, a range of loads projected from the amount of *problem water* defined by the SJV Drainage Program for year 2000 with and without implementation of the management plan (demand driven volume) in conjunction with a concentration of 50 μg/L Se (controlled concentration), yields a Se load range of 19,584 to 42,704 lbs Se per year. The various approaches converge on loads (rounded off) that range from 15,000 to 45,000 lbs per year.
- *Demand-driven load with minimum* management (45,000 to 128,000 lbs Se per year): This will occur if the demand for restoring saline soils drives drainage and neither quantity nor quality objectives can be (or are chosen to be) met. For example, a range of loads projected from the amount of *problem water* defined by the SJV Drainage Program for year 2000 without implementation of the management plan (demand driven volume) in conjunction with a concentration of 150 μg/L Se (non-controlled concentration), yields a Se load range of 42,704 to 128,112 lbs Se per year. This approach is likely to result in loads that exceed the managed maximum of 45,000 lbs per year and could approach as much as 128,000 lbs Se per year or even more.

Inputs of Selenium from Oil Refineries

The heavy crude oils that are produced in the SJV and refined in the Bay-Delta are especially enriched in Se (400 to 600 μg/L) (Cutter and San Diego-McGlone, 1990). So, refinery effluents have historically provided a quantitatively important load of Se to the Bay-Delta. Furthermore, the Se in these effluents is highly concentrated in a relatively small volume of wastewater, so inputs increase the ambient concentration of Se, especially around the Carquinez Strait (Cutter, 1989). In eight determinations of refinery effluents in 1987 and 1988, Cutter and San Diego-McGlone (1990) estimated that annual Se loadings could vary from 2,035 lbs per year to 4,641 lbs per year from all refineries combined. Annual loads from 1986 to 1992 ranged from 3,103 to 7,457 lbs Se per year as reported by the (Table 10) CSFBRWQCB (1993). In March 1988, refineries inputs accounted for 74% of the internal Se input to Bay-Delta; in May 1988, they accounted for 96%. Selenium inputs from refineries are relatively constant through the year, so they have their greatest influence on Se concentrations during the low river inflow season.

As a result of regulations imposed by the CSFBRWQCB, refinery inputs to the Bay-Delta declined after July 1998. The annual Se loads allowed for the five major refineries by state permit (CSFBRWQCB, personal communication, Johnston Lam and Khalil Abu-Saba, 2000) are listed in Table 10 in comparison to the annual range reported by the CSFBRWQCB from 1986 to 1992 (CSFBRWQCB, 1993). By this estimate, refinery inputs declined by about half (to approximately 2,200 lbs Se per year), from the amount measured from 1986 to 1992 (Cutter, 1989; Johns et al., 1988). On the other hand, refinery effluents also are regulated to concentrations of 50 μg/L Se and to the volumes discharged in the late 1980's. If volumes of effluent remain what they were in the late 1980's, the resulting Se load would be 1,400 lbs Se per year. Treatment technologies in the refineries also remove only selenite. So the Se discharged was, presumably, mostly selenate in 1999; historic discharges were >50% selenite. No mass balance model has yet been constructed to evaluate whether 1,400 lbs or 2,200 lbs Se per year best describe refinery discharges, but the difference is relatively small considering the variability within years and within refineries (Table 10). Preliminary data suggest the selenite concentration peak near the refineries disappeared after the treatment technologies were implemented (Cutter et al., in preparation).

Inputs of Selenium from the Sacramento River

Most of the river inflow to the Bay-Delta comes from the Sacramento River (Figure 5). The discharge ratio between the SJR (at Vernalis) and the Sacramento River (at Freeport) is typically 10 to 15%. The dissolved Se concentrations in the Sacramento River at Freeport are consistently low, averaging 0.06 ± 0.02 μg/L (Cutter and San Diego-McGlone, 1990). Thus, the Sacramento River represents a low concentration, high volume source of Se. Using a concentration of 0.04 μg/L Se (a conservative estimate) and the inflows given below, the projected annual Se loads conveyed by the Sacramento River to the Bay-Delta are:

- 32 MAF, wet year 3,482 lbs Se per year
- 17 MAF, median year 1,850 lbs Se per year
- 10 MAF, dry to critically dry year 1,088 lbs Se per year
- 5 MAF, most critically dry year 544 lbs Se per year

Selenium load increases with volume of inflow from the Sacramento River, because Se concentrations in the river are low but constant. The Sacramento River inflow therefore establishes the baseline flow and Se concentration entering the estuary.

Summary

In our model, four inputs in different proportions determine the Se load to the Bay-Delta. The Sacramento River loadings vary purely as function of inflow volumes (1,859 lbs Se per year, median precipitation year). The potential loadings from an extension of the SLD vary quite widely. Supply-driven loadings are lowest; demand-driven loadings with management and treatment capabilities fall within the range of 15,000 to 45,000 lbs Se per year. Loading rates escalate steeply if treatment strategies are not applied. Loadings from regulated concentrations in the SJR vary with the quantity of SJR water that reaches the Bay-Delta. The Se load from the SJR, at present, is 5,660 to 8,000 lbs Se per year, if considered separately and no recycling occurs. We assume oil refinery loadings will remain at post-1998 values reflecting regulation and treatment technology (approximately 1,400 to 2,200 per year). The sums of combinations of these scenarios represent the loadings under different management and hydraulic conditions. We will consider a few specific, most likely, scenarios for the Bay-Delta in detail for forecasting Se concentrations in water, sediment, and the food web and evaluating the ecological effects on predators (birds and fish) in the Bay-Delta estuary.

HYDRAULIC CONNECTIONS AND CONVEYANCE OF SELENIUM TO THE BAY-DELTA

The loads from the SJV can be conveyed to the Bay-Delta either via the SJR or via a proposed extension of the SLD. As discussed earlier, the originally planned valley-wide drain or SLD was a proposed canal that would collect irrigation drainage valley-wide or from the San Luis Unit (i.e., Westlands subarea and parts of what is now the Grassland subrea) and deposit it directly into Suisun Bay (Table 1; Figures 4 and 5; and Appendix A). If extensions of the SLD are constructed, the drain could potentially collect drainage from all five subareas of the western SJV or, as configured, from Westlands subarea and Grasslands subarea only and release it directly into the Bay-Delta.

The SJR is the only natural outlet from the SJV. A substantial proportion of the freshwater flowing toward Bay-Delta from its watershed is diverted (exported) for agricultural and urban uses. Before the 1990's, the inflows of the SJR were almost completely diverted and recycled. That meant little or none of the Se discharged into the SJR reached the Bay-Delta. After the 1994 Bay-Delta Water Accord (CSWRCB, 1994), water management changed; more Se will reach the Bay-Delta as less recycling of the SJR occurs. However, not all water that leaves the SJR at Vernalis enters the Delta or the Bay. The merging of the Sacramento River and SJR systems in the estuary and exports or water diversions add complexity (Figures 9 and 10). The amount of potentially Se-laden SJR inflow reaching specific locations in the Bay-Delta is influenced by (CSWRCB, 1999a; Monsen, 2000):

- tidal cycles;
- variable inflows of the Sacramento River and SJR due to seasons and upstream withdrawals;
- quantity of water diverted from the Delta to the CVP, SWP and local water users;
- discharge of agricultural drainage from the SJV and drainage inputs within the Delta itself;
- channel configurations and capacity; and
- artificial barriers which periodically are constructed to route flows in the Delta

Changes in both the channel configurations and barrier system are being proposed (CALFED, 1998a; b and 1999a; b; c; d).

Figures 9 and 10 show the balance for the Bay-Delta in a wet year (1996) and in a dry year (1994) among:

- total river (Sacramento River and SJR) inflow;
- SJR inflow;
- water diversions [i.e., pumping at Tracy and Clifton Court Forebay (CCtF) south to the Delta-Mendota Canal and the California Aqueduct]; and
- total outflow of the Bay to the Pacific Ocean.

Total inflows and SJR discharges are very high in the first five months of a wet year, far exceeding diversions. In the fall, however, water diversion can exceed total inflows. In September through November, SJR discharge at Vernalis can be a large proportion of total inflows. During this time of year, if SJR inflow is transported past the diversions, it can have a substantial influence on Bay-Delta waters. Manipulations of barriers, modification of the channels, or construction of alternative diversion facilities could all affect (or are affecting) whether or not SJR inflow reaches the Bay-Delta during this time of year. Better understanding of water movement from the SJR thorough the Bay-Delta and processes within the estuary are critical to future evaluations of Se issues. Evaluations of the implications of water management decisions must consider effects on Se transport and residence time. A large range of residence times have been estimated for freshwater in various parts of the Bay-Delta (Walters et al., 1985). The estimated residence times (days) for high flow periods/low flow periods are:

- Suisun Bay 0.5/35
- San Pablo Bay 0.8/25
- Northern reach 1.2/60
- South Bay 120/160
- South Bay (north of Dumbarton Bridge) 80/120
- Extreme South Bay (south of Dumbarton Bridge) 40/70

CONCENTRATIONS OF SELENIUM IN THE BAY-DELTA

Interpreting Effects of Source Water Se Loads on Receiving Water Se Concentrations

Interpretation of mass loadings from individual sources requires understanding how load and volume in different source waters combine to produce concentrations in receiving waters. It is concentration in receiving waters that determines biological impacts. So ultimately the interaction between source water loading and receiving water concentration must be understood.

Load will increase with increased volumes of drainage, given the characteristics of Se concentrations in the drainage (Figure 6). Load also increases with volumes of inflow from the Sacramento River, because Se concentrations in the river are low but constant. On the other hand, concentrations in the mixture of waters where the sources combine will be dependent upon the sum of the volumes of the sources and the masses of Se in each of those sources. Dissolved Se comprises 80 to 93% of the total Se (Cutter, 1989) in the Bay-Delta so loads based on total Se can be employed to derive concentrations of dissolved Se.

The volume of water (or the rivers) input to the Bay-Delta is determined by climate and water management. As a simplification, these inflows can be thought of collectively as the rivers, meaning the sum of the inflows of the Sacramento River and the SJR. Monitoring of Se concentrations in the Bay-Delta receiving waters must take into account the monthly, seasonal, and year-to-year variability of hydraulic discharge. A useful simplification is to consider the Bay-Delta watershed as characterized by a distinct seasonal cycle of high inflows from the rivers in January through approximately June, followed by lower inflows through the last six months of the calendar year (Conomos, 1979; Conomos et al., 1985). In contrast to water volumes, the mass of Se in anthropogenic effluents such as oil refinery effluents is not highly variable because both volumes and concentrations are relatively constant (CSWRCB, 1992a; b). Monthly load targets for discharge to the SJR from the Grassland subarea vary from 348 lbs Se to 1,066 lbs Se, with the largest loads discharged during February. Volumes of agricultural drainage discharged from the Grassland subarea in 1997 varied from 1,274 to 4,867 acre-feet per month with concentrations varying from 25 to 106 μg/L Se to enable a targeted load. The Westlands subarea during 1981 to 1985 discharged an average concentration of 330 to 430 μg/L Se and the volume ranged from 304 to 772 acre-feet per month. In all these cases, the degree of variability in volume will be small compared to the variability in river inflows.

As a result of the mixing of variable inflows from the rivers (mostly with low Se concentrations) and relatively constant anthropogenic inflows (with high Se concentrations) a strong seasonal fluctuation and year-to-year fluctuations of Se concentrations would be expected. The protocol for linking load and concentration under the current hydraulic and Se inflow conditions in the Bay-Delta is:

- *Composite Input Load = Sum Se loads from each input (six month season or monthly)*
- *Composite Input Volume = Sum volumes for each input (mainly inflows of Sacramento and SJR (six month season or monthly)*
- *Composite Se Input Concentration = Composite Input Load / Composite Input Volume*

In wet years (high precipitation), reduced Se concentrations are expected in Bay-Delta receiving waters; in dry years and dry seasons, concentrations in receiving waters will increase. Therefore, evaluations of Se impacts must consider the time periods before, after, and during low flow periods, because this is when the highest concentrations of Se will occur. The dry years and dry seasons will be the ecological bottleneck (the times that will drive impacts) with regard to Se. Factors such as residence times and exchanges within the Bay and Delta are also important, but the models necessary to understand these smaller scale effects (e.g. elevated concentrations near sources of input; detailed distribution within the Delta or Suisun Bay) are not adequately developed. Further development of hydrodynamic models (Cheng et al., 1993; Monsen, 2000; Burau and Monismith in preparation), multiple media mass balance models, and kinetic geochemical models are very important to defining detailed ecological effects of Se and resolutions to future Se problems.

Existing Concentrations in the Bay-Delta

Regional baseline

Dissolved Se concentrations are low (0.06 ± 0.02 μg Se/L) in the Sacramento River (at Freeport) (Cutter and San Diego-McGlone, 1990) and in the seawater (0.02 to 0.08 μg Se/L) with which it mixes (Cutter and Bruland, 1984) in all seasons. The regional Se baseline in the Bay-Delta is defined by mixing the Se concentrations in these two endmembers, as determined by a salinity gradient through the estuary (Figure 11). A more complex case is one of a composite freshwater endmember comprised of the Sacramento River, the SJR, and the refineries effluents. The regional baseline can be compared to a theoretical mixing line for which the Se endmember concentration in the freshwater composite represents anthropogenic sources. In Figure 11, the example mixing profile gives a Se concentration of 0.23 μg Se/L (Figure 11). The composite freshwater endmember concentration is calculated from annual Se loads and volumes in the Sacramento River at 20 MAF plus a refinery input of 4,400 lbs Se per year (typical conditions in a wet year before refinery cleanup). The 1997 gradient shows Se concentrations through the estuary as the average composite endmember is diluted as a function of salinity. This type of mixing model, which is driven by salinity, can forecast a range of expected Se concentrations in the Bay-Delta. This approach to modeling Bay-Delta Se inputs illustrates that variation in Se loads delivered by an endmember consisting only of the Sacramento River will not cause changes in average Se concentrations in the Bay-Delta. This is because average concentrations in the river are relatively constant (i.e., within the range of 0.04 to 0.08 μg/L Se). However, the sum of source input Se loads determines the Se concentration of the composite freshwater endmember.

Therefore, adding a low volume/high concentration source of Se to obtain the composite freshwater endmember Se concentration will cause changes in the Se concentrations in the estuary system.

The spatial details of observed Se distributions can be compared to theoretical distributions to draw conclusions about internal sources or trapping of the property within the estuary. The projected Se concentration in the theoretical composite freshwater endmember used above (i.e., 0.23 μg/L Se) is similar to the Se concentration observed in surveys of the estuary (see discussion below and Cutter et al., in preparation).

Concentrations observed in the Bay-Delta

Five studies have been conducted that have employed reliable analyses of dissolved Se distributions in the Bay-Delta. Cutter (1989) sampled the full salinity gradient of the North Bay in April and May 1986; Cutter and San Diego-McGlone (1990) repeated that study in October 1987, December 1987, March 1988 and May 1988. Cutter et al. (in preparation; unpublished data quoted in Luoma and Fisher, 1997) sampled the salinity gradient again in May 1995 and October 1996. The San Francisco Estuary Regional Monitoring Program since its inception in 1993 has also analyzed Se in the North Bay, although not as systematically along the salinity gradient (San Francisco Estuary Institute, 1993; 1994; 1995; 1996).

All surveys of the Bay-Delta report dissolved Se concentrations less than the 1 μg Se/L level designated as the Canadian wildlife hazard level (Environment Canada/Health Canada, 1995; Outridge et al., 1999); the 2 μg/L USFWS proposed chronic criterion for protection of aquatic life for all waters within the range of listed endangered species in the state of California (USFWS and NMFS, 1998 and amended, 2000); or the 5 μg Se/L USEPA chronic criterion for protection of aquatic life (derived from freshwater studies) (USEPA, 1992). The maximum concentrations of dissolved Se in most surveys are less than those observed in the adjacent watersheds (Cutter, 1989; Cutter and San Diego-McGlone, 1990; CCVRWQCB, 1992a; b; 1993) (Tables 2 and 5). Slightly higher concentrations are sometimes observed near the Golden Gate, but these appear to originate from the South Bay (Cutter, 1989). The highest dissolved Se concentration observed in any North Bay survey was 0.44 μg Se/L in August 1993 (San Francisco Estuary Institute, 1994). The lowest concentrations were observed in the Sacramento River in September 1986 and June 1995 (0.048 to 0.052 μg Se/L). No analyses have been conducted of Se concentrations in the Delta, although a recent CALFED supported study has begun some data collection in this area (Cutter et al., in preparation).

The spatial features of the Se gradient in the North Bay (Figure 12) were initially described by Cutter (1989). Surveys conducted between 1986 and 1996 show that Se concentrations are 1) highest in Suisun Bay, in the mid-salinity ranges near Carquinez Strait; and 2) lowest in the river and oceanic endmembers. This suggests a source of Se exists in the middle of the estuary. Cutter (1989) determined that the oil refineries were that source, an observation consistent with the distribution of biologically available Se reported by Johns et al., (1988).

Seasonal and year-to-year variations in the inflows from the rivers influence dissolved Se concentrations. Higher concentrations appear to occur during periods of low inflow than during periods of high inflows (Figure 12). Distributions also change with inflows from the rivers. In April 1986, after a very large flood in February, dissolved Se declined linearly from freshwater to seawater, correlating with salinity. Estimates of fluxes indicated that the export of Se from the Bay-Delta to the ocean was controlled by riverine sources during this month. During low flow seasons, dissolved Se concentrations increase and the peak in Suisun Bay becomes more distinct. Cutter (1989) and Cutter and San Diego-McGlone (1990) showed that in September 1986, total Se inputs from the rivers was 2.45 lbs per day (or extrapolated, 894 lbs Se per year) and total Se from internal sources was 17.9 lbs per day (or extrapolated, 6,534 lbs Se per year). Flux calculations from different sources indicated that the Se input from refineries were 2- to 8-times inputs from the rivers in this month, and were the cause of the shape of the gradient. In March of 1987, during a drought, refineries were 74% of the Se flux; in May 1987 they were 96%. Presumably, this has changed since July 1998; but only preliminary data are available.

Thus, while estuarine waters in the Bay-Delta are enriched in Se compared to the regional baseline, the Se concentrations in the estuarine waters are low compared to many contaminated freshwater environments. The concentration of dissolved Se among rivers and estuaries in England (Measures and Burton, 1978) and several rivers in eastern North America (Takayanagi and Cossa, 1985) range from 0.049 μg Se/L to 0.39 μg Se/L. Presumably some of these sites were anthropogenically contaminated like the Bay-Delta. This range is the same range as seen in the Bay-Delta. It is possible that physical or biogeochemical conditions in estuaries are the cause of these relatively low values. The challenge is to understand how these relatively low dissolved Se concentrations result in the degree of food web contamination described next.

CHEMICAL FORMS OF SELENIUM (SPECIATION)

Concentrations of waterborne Se are not sufficient to predict the biological implications of Se contamination. The geochemical speciation of Se is a critical consideration. Speciation of dissolved Se ultimately controls transformation reactions between dissolved and particulate forms (i.e. the reactions with sediments, detrital particles, and primary producers). Transformations and particulate concentrations are important factors determining the biological effects of Se; but they cannot be forecast without consideration of speciation.

Selenium is a natural trace element, number 34 on the periodic table, just below sulfur. Selenium can occur in three oxidation states in the dissolved phase:

- Organo-Se (-2 or -II) substituting for S^{-2} in proteins seleno-methionine and seleno-cysteine
- Selenite (+4 or IV) the oxyanion selenite (SeO_3^{-2}), an analog to the sulfur compound sulfite
- Selenate (+6 or VI), the oxyanion selenate (SeO_4^{-2}), an analog to the sulfur compound sulfate

Although dissolved Se in aerobic waters can sometimes occur predominantly as an organic form (Takayanagi and Wong, 1984; Cutter and Bruland, 1984), selenate and selenite are the most common forms in most waters. Selenate is the thermodynamically-predicted stable form of Se in oxic waters, but due to its slow oxidation rate in natural waters, selenite can be an important species (Cutter, 1982). Selenite is the most bioavailable of the dissolved phase inorganic species (Maier et al., 1993; Skorupa, 1998b). Comparative toxicity laboratory studies demonstrate that some forms of organo-Se are also very bioavailable and hence toxic to tested algae, invertebrates, and fish (Maier et al., 1993).

Examples exist in nature where each of the three major species of Se is predominant: 1) selenate predominates in most irrigation drainage inputs to wetlands (Presser and Ohlendorf, 1987; Zhang and Moore, 1996; 1997a; b); 2) selenite can predominate in systems affected by industrial wastes, especially those associated with wastes from fossil fuel products or consumption (Cutter and San Diego-McGlone, 1990); and 3) organo-Se can predominate where Se is strongly recycled (Takayanagi and Wong 1984). In the Bay-Delta, speciation differed among the source waters in 1980’s (Cutter and Diego-McGlone, 1990):

- Sacramento River inflow was 30 to 70% selenate, depending upon season; organo-Se was the other main component.
- SJR inflow was 70% selenate and 22% organo-Se.

- refinery wastewaters averaged 62% selenite.
- during low flow in Carquinez Strait, as much as 50% of the Se was selenite in the late 1980's, reflecting the predominance of refinery inputs.
- preliminary studies in Suisun Bay in the late 1990's showed less selenite, but selenite plus organo-Se could comprise 60% of the mass of Se.

PARTICULATE AND SEDIMENT-ASSOCIATED SELENIUM

Processes Affecting Particulate Selenium

Partitioning

One of the most important biogeochemical steps or links controlling the bioavailability and effects of Se is the partitioning reactions that determine the distribution between dissolved and particulate phases, where particulate phases include primary producers (e.g. phytoplankton), bacteria, detritus, suspended inorganic material and sediments. There are several reasons these reactions are important:

- The pathway for nearly all Se transfer to the second trophic level in the system is via particulate forms (i.e., animals bioaccumulate Se from their food to a much greater extent than they take up Se from water, at the distributions typical of nature, Luoma et al., 1992).
- The transformation efficiency from dissolved to particulate Se ultimately determines food web concentrations of the element (i.e., higher Se concentrations on particulate material means greater contamination in the food web, although the form of the Se in the particulate can also be important);
- Concentrations of Se on particulates can differ by as much as 100-fold, at the same dissolved concentration, depending upon the biogeochemical transformation reactions governing the dissolved particulate interaction. Thus, forecasts of effects depend upon understanding what transformations will occur.

The largest inventory of Se in a contaminated ecosystem usually occurs in sediments. For example, 90% of the inventory of Se in Kesterson National Wildlife Refuge was deposited in sediments (Tokunaga et al., 1996). However, the proportion of Se on suspended particles, at any one time, may be only a small fraction of the total *quantity* of Se in the water column. For example, in April 1986, Cutter (1989) found that only 7% of total Se in the water column of the North Bay was particulate; in September 1986, only 13 ± 7% was particulate. The large inventory of Se in sediments results either because suspended particulate Se is progressively deposited in sediments over time and/or because reactions within the sediments progressively strip Se from solution.

The concentration per unit mass on the particulate material is more critical than the mass in suspension (per unit volume of water). In fact, the most important measure of Se in any environment may be the concentration of Se per unit mass of suspended particulate material. This concentration determines the exposure of the many species that feed on such material. Each species' exposure to Se is partly determined by how that species "samples" the complex water/sediment/particulate/organism milieu that composes its environment. Many species are able to efficiently gather large quantities of particulate material from the water column, even when particulate concentrations themselves are relatively low. Bioaccumulation is then determined from the μg Se/g food or particulate material, along with the efficiency with which that concentration is assimilated (Luoma et al., 1992). Assimilation efficiency (AE) is the proportion of ingested Se that is taken up into tissues; and AE varies with the type of food or the form of particulate Se.

Direct determinations are rare of Se concentrations per unit mass on suspended sediments. This is at least partly a result of the difficult challenge of collecting a sufficient mass of suspended material for direct analysis.

Transformation

Several different primary reactions can transform (or affect transformation of) dissolved species of Se to particulate Se. Transformation reactions include biological, redox, and physical processes. The more important reactions are:

- *Assimilatory biological uptake and transformation*. In an oxygenated water column, a primary transformation is the biochemical transformation of Se(IV), Se(VI) and/or dissolved organo-Se [Se(-II)] to particulate Se(-II) via uptake by plants or, perhaps microorganisms. Microbes, plants, and microflora (phytoplankton) reduce the Se they concentrate to Se(-II). Most biochemically transformed Se is found within the cell solution, at least in phytoplankton (Reinfelder and Fisher, 1991), and is highly bioavailable to animals that consume the microorganisms for food. When cells die and breakdown the plants release both Se(IV) and

Se(-II) back to the water column in dissolved form. Biotransformed Se (-II) can also be sequestered in sediments or suspended particulate material, as detrital Se(-II).

- *Dissimilatory (extra-cellular) biogeochemical reduction.* When Se in water contacts reduced particles (little oxygen) or reduced sediments, sequestration onto or into sediments by bacteria can occur. The most important microbial transformation reaction under these conditions is dissimilatory reduction (Oremland et al., 1989). Dissimilatory reduction of either Se(IV) or Se(VI) generates predominantly elemental Se [Se(0)] in sediments; but it may also generate some operationally defined organo-Se [Schlekat et al., in press (b)]. Elemental Se can be further transformed within the sediments by reactions such as precipitation as ferroselite ($FeSe_2$), incorporation into solid phases such as pyrite (Velinsky and Cutter, 1991), or uptake by plants to ultimately form detrital organo-Se (Zhang and Moore, 1997a; c).
- *Oxidation state*. The particulate Se generated by the transformation reactions can occur in different oxidation states depending upon the transformation reaction and subsequent exposure to geochemical conditions. Understanding the form of particulate Se is critical to evaluating impacts of Se contamination, because each form has a different biological availability (Luoma et al., 1992). Reduction/oxidation status, determined by the balance of redox couples, is especially important in determining particulate form. Possible particulate forms include: adsorbed/coprecipitated selenite (SeIV) and selenate (SeVI), organic selenides, either in the form of intracellular Se(-II) or detrital Se(-II), or elemental Se (Se(0)).
- *Adsorption*. Geochemical adsorption can occur in the water column, if reduced sediments are mixed back into an oxygenated water column and oxidized (Dowdle and Oremland, 1999), or, perhaps, at the boundary of oxygenated and de-oxygenated conditions (the redox interface) (Tokunaga et al., 1997; 1998; Myneni et al., 1997).
- *Volatilization.* Biogeochemical volatilization of Se is well documented in wetland soils (Cooke and Bruland, 1987; Thompson-Eagle and Frankenburger, 1992) and in evaporation ponds (Fan and Higashi, 1998). Volatilization rates depend upon physical/chemical conditions, vegetation, water management or other rate limiting factors (Flury et al., 1997; Zhang and Moore, 1997a; c; Hansen et al., 1998). The influence of volatilization on Se concentrations in sediments (the relevance to this discussion) is determined by the mass of Se volatilized, compared to that in sediments. A careful mass balance including determination of Se inputs, outputs and internal inventories is the only way to verify effects of volatilization on

Se inventories. Studies that present a full complement of such analyses are rare; so significant uncertainties remain about the role of volatilization. Cooke and Bruland (1987) originally observed from limited data that approximately 30% of the incoming Se was volatilized at Kesterson Reservoir. Zhang and Moore (1997d) and Hansen et al. (1998) reported results consistent with that figure for other wetland systems. If this value of 30% is typical, it is possible to calculate the effect of volatilization on Se concentrations in a wetland that receives a continuous input of Se. If 90% of incoming dissolved Se is trapped in the sediments, and if 30% of that is volatilized, then the net effect of volatilization is to reduce the progressive accumulation of Se in particulate material to: 0.90 trapped X 0.30 volatilized = 0.63 trapped X 100 = 63% of incoming Se retained. Thus volatilization could slow Se accumulation to a rate less than would otherwise be achieved. However, in no known case has volatilization eliminated Se contamination or alleviated water quality problems. Wetland trapping can remove Se from contaminated waters, but most of the Se remains in the sediments; efforts to completely volatilize Se to the atmosphere have not proven successful. If Se inputs to the wetland were eliminated, eventual removal by volatilization is a theoretical possibility. However, this also has never been observed in natural sediment with a high Se load (e.g., Flury et al., 1997).

Range of distribution coefficients (Kd's)

The distribution coefficient (Kd) is a way to quantitatively describe the partitioning of total Se between dissolved and particulate states. The Kd is the ratio of Se per unit mass particulate material versus Se per unit volume water, in equivalent units. An example of a calculated Kd for the Bay-Delta from typical 1986 data (Cutter, 1989) is:

(700 μg particulate Se/kg particulate)/(0.315 μg dissolved Se/L) = 2.2×10^3 L/kg.

Speciation of dissolved Se and transformation reactions have a combined influence on the distribution coefficient of Se. The Kd oversimplifies both with the result that Kd's based upon total concentrations in natural waters vary by as much as two orders of magnitude. Nevertheless, the Kd is a first order measure of partitioning and employs the data most widely available from a variety of systems. Table 11 lists Kd's typical of the variety of ecosystem from which reliable geochemical data are available. The Kd's in various field studies have ranged from 0.3×10^3 to 2×10^4, reflecting the complicated transformation reactions and processes described above. Skorupa (1998a) also summarized the range of dissolved and sediment data found in various field studies. Median Kd's from that list, although not calculated by Skorupa (1998a), show a similar range. The range of Kd's allows understanding of the potential range of particulate Se concentrations that could occur in the Bay-Delta under different partitioning conditions in the absence of site-specific biogeochemical models.

Sources of Particulate Selenium in the Bay-Delta

The general sources of particulate Se in the Bay-Delta include:

- *Autochthonous (internal) sources in the SJR or the Delta (external to the Bay-Delta)*: Selenium could be transformed to particulate forms in the marshes of the SJR and the wetland/lakes of the Delta by either dissimilatory reduction to Se(0) or biotransformation to Se(-II). Very little is yet known about Se trapping or transformation within the Delta itself.
- *Allochthonous (external) sources*: It is possible that Se contaminated particles produced in the SJR could be transported to and trapped in the Delta. Particulate Se transformed within the Delta may be transported to the Bay-Delta, although the conditions under which such transport would occur are not well known. Any drain carrying irrigation return water to the Bay-Delta will contain externally and internally produced particulate Se.
- *Autochthonous sources in Suisun Bay*: Long hydraulic residence times occur in Suisun Bay, as inflows recede or during low inflows. Longer residence times progressively increase the likelihood for biotransformation by local microflora and microbes in the water column, on surface sediments or within sediments (Lemly, 1997a).

Long residence times and contact between the water column and the redox interface in sediments are critical factors in progressively accumulating Se in the sediments of wetlands or shallow waters (Zhang and Moore, 1997a; b). Thus the time of greatest vulnerability in the Bay or Delta are low inflow seasons and low inflow years when residence times are longest. The places most likely to generate particulate Se are wetlands and shallows with long residence times. Restoration activities could affect Se contamination in the SJR-Bay-Delta system if they change hydraulic residence times or generate a larger area of the kinds of systems that trap Se, without remediating Se inflows.

Particulate selenium in the San Joaquin River

Direct inputs of irrigation drainage to the SJR have long occurred, via canals and wetlands. Since 1996, the SLD has also directly discharged drainage from the Grassland subarea to the river.

Difficulties arise in drawing generalizations about temporal trends or spatial distributions of particulate Se in the SJR, however, because there are few consistent, extensive or systematic surveys. Where such surveys exist, sampling methodologies do not allow elimination of biases caused by changes in river discharge, concentrations of suspended material, Se concentrations on suspended material in different seasons or bed sediment characteristics like particle size and differences in organic carbon concentrations. A detailed, systematic and carefully designed study of particulate Se occurrence and trends would be relatively easy to implement and is badly needed. The existing data (Appendix E, Tables E1 and E2) show the following:

- *Upstream of SLD*: Concentrations of Se were 0.01 to <0.18 µg Se/g dw in sediments from upstream of the SLD discharge, in the SJR at Lander Avenue in 1987 - 1989. These are probably baseline concentrations of Se for the system. In 1993-1996 and 1997, concentrations upstream of the SLD discharge, in Mud Slough, were within the range: 0.10 to 0.44 µg Se/g dw; the higher values probably reflect contamination from historic Se inputs to the slough.
- *Downstream of SLD, before 1996 discharges*: The range of concentrations, among several *ad hoc* studies, in sediments of the SJR downstream of the inactive discharge site (pre-1996) was 0.3 to 1.9 µg Se/g dw. One value of 5.2 µg Se/g dw was reported from the SJR near Vernalis.
- *Downstream after current operations began*: In September 1996, after operation of the SLD began, Se concentrations of 0.1 to 0.76 µg Se/g dw were determined in sediments immediately below the discharge, in Mud Slough. Concentrations 6.6 miles downstream from the discharge were 0.7 to 1.9 µg Se/g dw. Recent data show Se increasing to 4.8 µg/g dw in sediments in a seasonal backwater tributary of Mud Slough where residence time increases (USBR et al., 1999).
- *Suspended sediments*. Several surveys also have analyzed suspended sediments in the SJR or adjacent marshes or sloughs. In all cases, concentrations in suspended sediments exceeded concentrations in bed sediments. In a backwater where stagnant conditions would be expected (high hydraulic residence time), a concentration of 4.4 µg Se/g dw was determined. The range of concentrations in suspended sediments was 0.91 to 6.7 µg Se/g dw. Systematic studies of seasonality, relationships to hydrology or forms of Se could be instructive with regard to sources and causes of the large range of variability.

Particulate selenium in the Delta

Little is known about Se concentrations in the Delta. In 1986-88, Johns et al. (1988) sampled *Corbicula* and sediments near-monthly at a station in the Old River channel near Clifton Court Forebay. At that time and location, Se concentrations in both indicators (*Corbicula* sp., mean 3.1 µg Se/g dw and particulates grand mean, 0.19 ± 0.03 µg Se/g, dw) were significantly lower than found within Suisun Bay (*Corbicula* sp., range of means, 3.9 to 5.2 µg Se/g dw and particulates range of grand means 0.23 to 0.53 µg Se/g dw); and similar to concentrations found in the un-enriched Tuolumne River, which drains the Se-poor geology of the eastern San Joaquin Valley. No systematic Se studies were conducted in the Delta after SJR inflows to the Delta increased in the mid-1990's. The lack of study in Delta wetlands or shallow waters leaves open the question of whether Se can be sequestered there, at least in some locations.

Particulate selenium in existing portion of the San Luis Drain

Transport, re-suspension and re-oxidation of the particulate material in the existing SLD, if extended, might also be a source of bioavailable particulate Se to the Bay-Delta. Transformation of dissolved Se(VI) into particulate Se has been demonstrated within the existing SLD. Early surveys conducted when the SLD was carrying Westlands subarea drainage to the Kesterson National Wildlife Refuge observed a maximum sediment concentration of 210 µg Se/g dw and an average of 84 µg Se/g dw in the SLD (Presser et al., 1996; Appendix E, Table E1). A compilation of 1994 surveys, after the Grassland Bypass Channel Project had begun, showed a maximum of 146 µg Se/g dw and an average of 44 µg Se/g dw in SLD sediment samples (Appendix E, Table E1). In whole core samples collected in 1997 from the SLD, the range of concentrations was 3.8 to 100 µg Se/g and the mean was 30 µg Se/g dw (USBR et al., 1998). The elevated Se concentrations and the wide range of concentrations documented in bed sediment of the SLD are consistent with observations from wetlands (including Kesterson Reservoir) where microbial dissimilatory reduction and biotransformation by primary producers stripped dissolved Se from the water and converted it to particulate Se(0) and particulate Se(-II). Martens and Suarez (1997) showed that Se in SLD sediment was probably approximately 90% elemental Se, also suggestive that microbial dissimilatory reduction was especially important in that environment. Contact may occur within the drain between oxidized water and a sharp redox gradient in sediments, which is apparently sufficient to transform a significant quantity of incoming Se to particulate form (Presser et al., 1996; Presser and Piper, 1998). Re-suspension and transport of sediments from the SLD, therefore, must be considered as a source of Se for the SJR, deserving of further study. Similarly, re-suspension of sediments in a SLD extension to the Bay-Delta could provide a similar direct source of highly contaminated particulate Se to the Bay-Delta. The hydraulic residence time of the North Bay at low flows is about 60 days (Walters et al., 1985). Substantial oxidation of Se(0) could occur if fine particles or plant detritus generated in the SLD were transported to the Bay-Delta. Elemental Se might also be expected in sediments in the Bay-Delta where conditions favor biogeochemical deposition (anoxic sediments). Such conditions might be present in marshes near any discharge from a SLD extension or within sediments deposited within the SLD itself.

None of the sampling protocols referenced above included sampling of algal mats as part of the suspended or bed sediment fraction. Seasonal algal blooms occur in drainage canals and sloughs receiving agricultural drainage. Data collected during the discharge of the SLD into Kesterson National Wildlife Refuge showed that Se was concentrated in algal mats associated with evaporation ponds (Presser and Ohlendorf, 1987). Thus, algal mats and blooms may represent a significant fraction of total Se in an aquatic ecosystem from a mass balance basis that has not been systematically documented during surveys of suspended or bed sediment. The surficial layer of bed sediment may be the most affected by accumulations of decaying organic material (Presser et al., 1996)

Sedimentary selenium in Suisun Bay and San Pablo Bay

Wetland transformation of Se in the Bay-Delta has not been well studied, nor have surveys of marsh sediments been conducted systematically. Zawislanski and McGrath (1997) reported concentrations of 1.0 to 1.25 μg Se/g in the sediments of a marsh on Carquinez Strait. Concentrations were similar in core samples collected down to 15 cm depth in the sediment. Compared to dissolved concentrations in Carquinez Strait (0.1 to 0.3 μg Se/L), the Kd for the marsh sediments varied from 3.33×10^3 to 1.25×10^4. Zawislanski and McGrath (1997) also reported pore water concentrations of 2 to 10 μg Se/L, but further verification of such high values is necessary.

Bed sediments that have been studied to date in shallow water habitats of the Bay-Delta are not heavily contaminated with Se. For example, Se concentrations were determined in fine-grained sediments from a core collected in Richardson Bay, near the mouth of the estuary (Hornberger et al., 1999). Concentrations of Se (0.2 to 0.4 μg Se/g dw) were similar throughout the length of the core, with no clear anthropogenic signal accumulating in recent sediments.

Zawislanski and McGrath (1997) reported concentrations of 0.5 to 1.0 μg Se/g in mudflat sediments adjacent to a marsh in Carquinez Strait. Johns et al. (1988) found mean concentrations of 0.31 μg Se/g in repeated analyses of sediments from four locations in Suisun Bay in the late 1984 to 1986. Concentrations in New York Slough, where the SJR enters Suisun Bay, were the highest in the region (0.53 ± 0.28 μg Se/g dw) and varied, the most widely of any station, from 0.2 to 1.0 μg Se/g dw. Recent studies by Cutter et al. (in preparation) show results across a range similar to those reported by Johns et al (1988). In summary, concentrations of Se in fine-grained Suisun Bay sediments are approximately 0.3 to 0.5 μg Se/g dw and median concentrations of dissolved Se are 0.2 μg Se/L. These data show that the sediment water distribution coefficient is approximately 1.5 to 2.5 X 10^3, within the range reported for other ecosystems.

Suspended particulate selenium in Suisun Bay and San Pablo Bay

Water column biogenic transformation of dissolved to particulate Se is well known and is especially important in determining exposures of filter-feeding consumer organisms. Selenium concentrations per unit mass suspended material exceed concentrations in bed sediments, based upon several analyses conducted in 1986 (Cutter, 1989), June 1995 and October 1996. The concentrations on suspended material can vary widely.

- In April 1986, after an episode of extremely high river inflows, the maximum concentration of Se on particulate material near Carquinez Strait was 0.64 μg Se/g dw particulate and an average concentration throughout the North Bay was 0.33 μg Se/g dw particulate.
- In September 1986, during low inflows, the concentration of particulate Se averaged 0.75 μg/g dw, with a maximum of approximately 1.25 μg/g dw. The particulate Se concentrations were approximately 5 X 10^3 to 1 X10^4 greater than the concentration per unit mass dissolved in the water column.
- In June 1995, during a prolonged period of very high inflows, particulate Se concentrations ranged from 0.53 to 0.99 μg Se/g dw with an average concentration among six samples of 0.68 μg Se/g dw. The Kd for median concentrations in this sampling was:

$$[0.075\ \mu g\ Se/L] / [0.75\ \mu g\ Se/g\ dw] = 1 \times 10^4.$$

- In October 1996, during low flows, particulate Se concentrations were more than twice the concentrations in September 1986 (Figure 13). Concentrations of approximately 7.70 μg Se/g dw were observed in suspended material in the Sacramento River channel at Rio Vista and 3.57 μg Se/g dw was found in the SJR channel. The two are interconnected at this time of year, so the SJR was the likely source of this material. Concentrations declined down the estuary, further suggesting a delta/riverine source. Elsewhere in the Bay-Delta, Se concentrations on suspended material were approximately 1.54 to 2.51 μg Se/g dw, with an average concentration in eight bay samples of 1.98 μg Se/g dw [i.e., more than two times higher than the mean (0.75 μg Se/g dw) in September 1986]. The Kd's for the median Suisun Bay concentrations for the October 1996 survey were therefore:

$$[0.18\ \mu g\ Se/L] / [2.1\ \mu g\ Se/g\ dw] = 1.17 \times 10^4$$

- For the landward site at the head of the estuary with highly elevated concentrations, the Kd was:

$$[0.18\ \mu g\ Se/L] / [5.6\ \mu g\ Se/g\ dw] = 3.1 \times 10^4.$$

Summary

Concentrations > 1 μg Se/g dw in suspended materials are common and concentrations as high as 8 μg Se/g dw are observed in a few instances. The sources and frequency of the highest concentrations are not clear. Kd's in these surveys are consistently $\geq 1 \times 10^4$. The roles of factors such as particle size, organic content, and different transformation processes need to be better understood to resolve causes of the differences between suspended and sedimentary Se and the differences in Kd's between these two reservoirs of Se. Time-intensive studies and continued assessment of the sources of the highest Se concentrations transported in suspended material to the Bay-Delta are also needed.

BIOACCUMULATION OF SELENIUM BY INVERTEBRATES

Processes

Bioaccumulation by lower trophic level invertebrates (e.g., zooplankton and bivalves) is a critical step in determining effects of Se. These are the animals that provide the vector (food) that is the source of Se exposure to higher trophic level predators such as fish and birds. Estuarine invertebrates are exposed to Se via:

- direct uptake of dissolved Se;

- primary producers taking up Se and they themselves being consumed by animals: and/or
- direct uptake of detrital or sedimentary Se-enriched particles via filter-feeding or deposit feeding.

In laboratory studies of the muscle *Mytilus edulis*, dissolved selenite [Se(IV)] is the most bioavailable form of inorganic Se taken up from solution, but the uptake rate is slow compared to many trace elements (Wang et al., 1996). Luoma et al. (1992) showed that the uptake rate of dissolved selenite explained less than 5% of the tissue burden of Se accumulated by the clam *Macoma balthica* at concentrations typical of the Bay-Delta. The role of dissolved organic selenides in Se bioaccumulation is not as well understood as availability of inorganic Se, but it is unlikely that the rate of uptake is sufficient to be greater than uptake rates from food.

The evidence is strong that uptake of dissolved Se (dissolved selenite plus dissolved organo-Se) by invertebrates is not as important as uptake from diet (Luoma et al., 1992; Lemly, 1993 a). Dissolved Se speciation strongly influences uptake by primary producers (e.g. phytoplankton) and microbes. Uptake of selenite by phytoplankton is substantially more efficient than uptake of selenate. But if selenate concentrations are 10-times those of selenite, and uptake rates differ by 10-times, then the two forms could be equally important. Concentration factors by phytoplankton, for selenite, can be as high as approximately 10^4 or 10^5 (e.g., Butler and Peterson, 1967; Fowler and Benayoun, 1976; Wrench and Measures, 1982). Once taken up, selenite is incorporated into seleno-amino acids within phytoplankton (Wrench, 1978), which are then transferred to the next trophic level with great efficiency. Assimilation efficiencies for phytoplankton-associated Se vary from 55 to 90% among different invertebrates (e.g., Reinfelder et al., 1997). Selenium uptake from non-living particulate material or detritus has not been well studied. In general, it is probably less efficient than uptake from living plant material; although some fraction of most natural forms appears to be bioavailable (Wang et al., 1996; Luoma et al., 1992). For example, Luoma et al. (1992) studied uptake of particulate elemental Se produced from the microbial reduction of ^{75}Se-selenate. The particulate Se(0) was formed by simulating the biogeochemical transformation process thought to be predominant in wetlands. The assimilation efficiency of elemental Se was 22%.

Selenium in Invertebrates from the Bay-Delta

Fish and birds are the wildlife of greatest concern with regard to Se contamination. However, fish and birds are mobile, impractical to sample in large numbers, and difficult to monitor routinely. On the other hand, consumption of prey, comprised of primary and secondary consumer species, is the route by which these predators are exposed to Se. Consumer species like bivalves, polychaetes, amphipods or zooplankton can be practical to employ as resident bioindicators of Se exposure (Phillips and Rainbow, 1993; Brown and Luoma, 1995b). As discussed below, the predators with the highest tissue concentrations of Se in the Bay-Delta are benthivores that consume bivalves in their diet. Therefore, the most relevant bioindicators to these sensitive predator species are bivalves.

Interpretations are least ambiguous when Se concentrations in bioindicator species are compared to clearly defined reference concentrations. For our model, we assume that a location is an adequate reference if soils or geology are not Se-enriched, if no anthropogenic sources of Se are known, and if the concentrations in the indicator organism are in the lowest quartile of all available data. Concentrations of 1.70 μg Se/g to 2.66 μg Se/g dw were reported by the *San Francisco Estuary Regional Monitoring Program for Trace Substances* during 1993 to 1995 for the clam *C. fluminea* transplanted from a clean environment to the Sacramento River (San Francisco Estuary Institute, 1994; 1995; 1996). Johns et al. (1988) found a mean reference concentration and 95% confidence limits of 3.08 ± 0.28 μg Se/g dw in *C. fluminea* from apparently uncontaminated sites near Clifton Court Forebay and in the Tuolomne River (Figure 14a).

Bivalves from the Bay-Delta have elevated Se concentrations compared to these references (Risebrough et al., 1977; Johns et al., 1988; Urquhart and Regalado, 1991) (Figure 14a). Risebrough et al. (1977) reported concentrations of 10.0 to 11.4 μg Se/g dw in a single deployment of transplanted mussels (*Mytilus sp.*) in Carquinez Strait, and concentrations of 5.0 to 7.4 μg Se/g dw near Mare Island in Suisun Bay. Anderlini et al. (1975) reported concentrations of 4.5 to 6.7 μg Se/g dw in the clam *M. balthica* near Mare Island in 1974. Although conducted more than 20 years ago, both these studies analyzed their samples by neutron activation, which is a relatively insensitive but reliable analytical technique. Johns et al. (1988) collected *C. fluminea* from resident populations at six locations in Suisun Bay, between January 1985 and October 1986. Figure 14a compares the frequency distribution in 129 composite samples of *C. fluminea* collected from the sites nearest Carquinez Strait (Roe Island and Middle Ground) to the reference values reported by Johns et al. (1988). The mean concentration and 95% confidence limits among the Suisun Bay data was 5.08 ± 0.17 μg/g dw, significantly different than the reference values ($p<0.001$). These historic data show that the habitat in Carquinez Strait was contaminated two-fold or more with Se compared to reasonable reference locations, and that contamination was present since at least 1974.

In 1986, the bivalve *Potamocorbula amurensis* invaded the Bay-Delta. This species was previously known only in the estuaries of Northeastern China, Korea and Japan. *P. amurensis* eventually replaced several other resident species in Suisun Bay after the invasion, and is probably now the dominant food of benthivore predators in the ecosystem (Nichols et al., 1990). Figure 14b adds to the *C. fluminea* distribution, the frequency distribution of Se among 62 composite samples of *P. amurensis*, collected between May 1995 and June 1997, from Carquinez Strait (Linville and Luoma, in press). The mean concentration and 95% confidence limits among all data for *P. amurensis* was 12.94 ± 0.75 µg/g dw. A wide distribution of concentrations was also observed, reflecting substantial temporal variability.

Thus, the mean concentration of Se in the dominant resident bivalve in Suisun Bay (*C. fluminea* in 1985-86 compared to *P. amurensis* in 1996) has more than doubled since 1985-86. It is therefore likely that the total amount of Se experienced by birds and fish that feed on bivalves has similarly doubled. The 1995-1997 mean concentration in *P. amurensis* exceeds the dietary threshold (10 µg Se/g dw) for predators that has a high certainty of producing adverse effects in predators. During 1995 - 1997, 32% of *P. amurensis* samples from Carquinez Strait contained greater than 15 µg Se/g dw. Lemly (1997a; b; c) cites case studies that indicate that concentrations of Se in prey species of 5 to 20 µg Se/g dw initiate teratogenic deformities in fish and load the eggs of some bird species beyond teratogenic thresholds (see discussion below).

Se concentrations in *P. amurensis* from Carquinez Strait vary seasonally. Concentrations varied approximately three-fold with time during 1995 to 1997. The highest concentrations were observed in October 1996 (20 ± 1 µg/g dw) and the lowest concentrations were observed in May 1995 (7.13 ± 0.34 µg Se/g) and May 1997 (6.2 ± 0.2 µg/g) (Figure 15). The changes in concentrations coincided with seasonal changes in mean monthly river inflows to the North Bay. The lowest concentrations occurred after the two episodes of highest river inflows. The greatest increase in Se occurred after prolonged periods of low flow. Inflows from the SJR and/or inflow-driven differences in residence times of local waters could also be important, because the highest ratios of SJR/total Delta outflow occur in fall (Figures 9 and 10).

An extensive spatial survey was conducted in October 1996 to determine how concentrations of Se in *P. amurensis* compare among different locations in the North Bay. Se concentrations were determined in replicate composite samples of *P. amurensis* at 22 locations (Figure 16) (Brown and Luoma, 1995a; Linville and Luoma, in press). The October 1996 sampling included an extensive investigation of the shallow habitats adjacent to marshes and mudflats of San Pablo Bay and Suisun Bay, as well as deeper channel stations. Selenium enrichment, compared to historic concentrations in previously dominant benthos, was widespread throughout the North Bay; with all concentrations in *P. amurensis* in excess of those in *C. fluminea* observed by Johns et al. (1988). Among the stations, the greatest elevation of Se was found in resident *P. amurensis* from Carquinez Strait and from the deeper, westward channel of Suisun Bay and toward the mouth of the SJR. Selenium concentrations in *P. amurensis* from the shallows, adjacent to marshes in Honker Bay were higher than concentrations in Grizzly Bay and San Pablo Bay. The two sites with the lowest mean concentrations were found in Grizzly Bay, in particular in association with inflows of Sacramento River water through a location called Suisun Cutoff.

Summary of Selenium in Invertebrates from the Bay-Delta

In summary, Se bioaccumulation data from invertebrates show the following:

- Selenium enrichment in primary consumer species (bivalves) has been evident in Suisun Bay since the 1970's.
- The spatial pattern of historic contamination was consistent with an origin from refinery effluents (as shown by water column analyses), which have been discharged to the Bay-Delta since approximately 1900.
- The highest Se concentrations reported in the Bay-Delta in consumer organisms in a species of bivalve that is now the dominant benthic species in Suisun Bay were found in the 1995 to 1997 studies of Linville and Luoma (in press). No systematic studies of Se concentrations in clams are available since that time.
- Selenium enrichment was apparently spread through all of Suisun Bay and all of San Pablo Bay in 1996.
- Temporal variability was not significant in monthly samples of *C. fluminea* in 1985-86; but three-fold seasonal variability in Se concentrations is now observed in *P. amurensis* near Carquinez Strait. Concentrations in *P. amurensis* increased during low river inflow regimes, decreased during higher river inflow regimes

- In the most recent survey, Se concentrations in *P. amurensis* near Carquinez Strait exceed 10 μg/g dw in most months of the year (all months of some years), and 32% of values measured between October 1995 and June 1997, exceed 15 μg/g dw. Thus, thresholds for chronic Se toxicity in the food of birds and fish (> 10 μg/g, Skorupa, 1998a) are exceeded regularly.
- It is not yet clear whether the high Se contamination in *P. amurensis* is unique to this species, represents greater Se inputs (probably from the Delta and SJV via the SJR) than occurred historically, or both.

Modeling Selenium Bioaccumulation in the Bay-Delta: DynBaM

Bioavailability of Se is affected by a variety of factors. Models are the most effective forecasting tool to encompass a range of factors involving a range of assumptions. Realistic exposure models need to be geochemically robust (i.e., include consideration of geochemical form), biologically specific, and flexible for a variety of environmental circumstances. Predictions from the model should be verifiable in nature. The USEPA approach (Peterson and Nebeker, 1992) uses the following simple ratio:

Bioaccumulation = [concentration in organism]/[concentration in environment],

where environmental concentrations are either those in water (the BAF, bioaccumulation factor) or sediment (the BSAF, biota to sediment accumulation factor).

The flaw of this approach is that it does not allow consideration of effects of speciation in water or of particulate material on bioaccumulation. Thus BAF's can vary by as much as 50-fold for a given species in different environments, and much more than that among species. An alternative modeling approach, the *Dynamic Multi-pathway Bioaccumulation Model* or *DynBaM* uses different experimentally established uptake rates for different forms of dissolved and particulate Se, along with environmental concentrations of these forms, to determine bioaccumulation in tissues (Luoma et al., 1992). The advantages of this approach have been discussed extensively by Luoma and Fisher (1997) and Schlekat et al. [in press (a)]. One advantage for the Bay-Delta evaluation is that bioaccumulation can be derived for different speciation regimes. The speciation consideration is very important because speciation will change as sources change, and relations with total Se or individual species of Se will also change (e.g., CSFBRWQCB, 1992a). Another substantial advantage of the approach is that model predictions can be verified by comparison to analyses of Se in tissues of resident species. We will employ *DynBaM* in all predictions of Se effects on predators from forecasts of Se loadings.

The mathematics of the simplest kinetic model with food and water pathways illustrates the necessary data:

$$dC_m/dt = (I_f + I_w) - C(k_e + g) \quad (1)$$

$$C_{m,t} = [I_f + I_w/(k_e + g)] [1 - e^{-(kt + g)t}] \quad (2)$$

$$C_{m,ss} = I_f/k_e \quad (3)$$

where, C_m is concentration in animal, t is time, I_f is gross influx rate from food, I_w is gross influx rate from water, k_e is rate constant of loss (slowest compartment), and g is growth. For $C_{m,ss}$ or concentration at steady state

$$C_{m,ss} = I_f + I_w/k_e \quad (4)$$

if we assume that growth is not important. Mechanistically, the mathematics state that bioaccumulation results from a combination of gross influx rate as balanced by the gross efflux rate. Gross efflux is an instantaneous function of the concentration in tissues and the rate constant(s) of loss (Equation 1, 2). Gross influx can come from water or from food and is a species-specific function of the concentration of bioavailable element.

For influx rate from food alone, in μg Se/g tissue per day:

$$I_f = FR \ X \ C_f \ X \ AE \quad (5)$$

where FR is feeding rate in g food/g tissue per day, C_f is concentration in food (particulate material) in g Se/g dw, and AE is assimilation efficiency. Influx rate from water can be broken into its components similarly (Wang et al, 1996), but because the influx rate from water was determined experimentally for specific species of Se by Fowler and Benayoun (1976), Wang et al. (1996) and Luoma et al. (1992), the rate will be employed directly here as μg Se/g tissue per day.

From Reinfelder et al. (1997), the ultimate concentration of Se that a bivalve would bioaccumulate under each environmental condition can be calculated from:

$$C_{ss} = [Iw + (FR \ X \ C_f \ X \ AE)]/k_e \quad (6)$$

BIOACCUMULATION OF SELENIUM BY PREDATORS

Numerous studies have demonstrated that a small increase in waterborne Se will result in a disproportionately large elevation of Se concentrations in fish and wildlife (Skorupa, 1998a). Several attributes affect Se uptake by these organisms:

- Processes that affect Se retention and inter-organ distribution are important considerations for fish and birds that range and feed widely over areas with varying Se exposure pathways.
- Dietary exposure and, in most cases, progressive biomagnification through the food web is the pathway that leads to the disproportionately large bioaccumulation of Se in upper trophic levels.
- Some implications of dietary uptake are:
    - waterborne Se concentrations are poorly linked to predator bioaccumulation because environmental factors affect transformation of Se and uptake by invertebrates;
    - where data on predators is difficult to obtain directly, invertebrates may be the best indicator for monitoring predator exposures;
    - a predator's choice of food, which varies widely among species, could result in some trophic pathways being more efficient accumulators of Se than others. For example, long-term studies of the terrestrial environment created by burial of the contaminated evaporation ponds at Kesterson Reservoir show that invertebrate carnivorous and scavenger species tend to be higher than herbivorous species as a route to vertebrate exposure (CH2M HILL, 1996; 1999a).

Dietary Exposure

Lemly (1982; 1985) was one of the first to show that dietary uptake was responsible for the largest proportion of bioaccumulated Se in fish. This study was at a reservoir (Belews Lake, North Carolina) contaminated by the wastes of a coal-fired power plant (Cumbie and Van Horn, 1978). He compared concentrations of Se in bluegill and largemouth bass collected from the lake, with concentrations of Se in those species when exposed to sublethal concentrations of Se in water alone in a laboratory study. He found a lower concentration factor from water alone than from bioaccumulation via dietary plus waterborne sources. This finding was corroborated by the observation that piscivorous fish, at the highest trophic level, accumulated the most Se in the lake. All piscivores and omnivores eventually succumbed to the poisoning, while a few lower trophic level fish survived. Other studies have since verified directly and indirectly the overwhelming importance of Se bioaccumulation from food, as compared to direct uptake from water.

If the primary source of Se to wildlife is dietary, then it should not be surprising that waterborne or dissolved Se is an imprecise predictor of the Se exposure of birds and fish (Skorupa and Ohlendorf, 1991). Differences in speciation, transformation to particulate form(s), speciation on particulates and invertebrate bioaccumulation all influence how waterborne Se is transferred to a predator. These processes are affected by the nature of the source and the environmental conditions in receiving waters (e.g. Se in agricultural drainage water can be a different form than the Se in industrial sources; Se discharged to a wetland is transformed differently than Se discharged to an estuarine water column). Physical processes like hydraulic residence time are also important. Particulate transformation of Se in a river (e.g. the SJR) may occur far downstream from the source of input; while transformations in a wetland or an estuary with a long residence time may occur near the input. Biological processes that affect exposure of the predator include differences among predator species in feeding, behavior, and physiology.

An example of the influence of confounding processes on this linkage can be found in data from the Bay-Delta watershed. Black-necked stilt, a wading bird, averaged about the same exposure to Se (20 to 30 μg Se/g dw found in eggs) at Chevron Marsh in the Bay-Delta as at Kesterson Reservoir (25 to 37 μg Se/g dw in eggs), but the source water in Chevron Marsh contained about 10% the concentration of Se found at Kesterson (maximums: 20 vs. 300 μg Se/L) (Skorupa, 1998a). The reason for the difference was that the transfer of Se from water to aquatic invertebrates was greatly enhanced at Chevron, compared to Kesterson, because the original form of the element was selenite.

Because of the above complexities, the strongest correlative predictor of Se concentrations in predator tissue that reflects Se exposures is probably Se concentrations in invertebrates (prey). Invertebrates may be the optimal indicator to use in monitoring Se in an ecosystem because they are practical to sample and are most closely linked to predator exposure (prey are the primary source of Se for the predators). Few authors have fully explored feeding relationships and resultant correlations with Se bioaccumulation in food webs.

One repeated observation in contaminated ecosystems is that predator species differ in their bioaccumulation of Se. In general, this variable accumulation seems to be related to the diet of the predators. In Belews Lake, concentrations followed the ranking: piscivores (bass and perch) >

omnivores > planktivores. These feeding guilds were probably too broad, however. In Lake Oltertjarn, Sweden, after treating the lake with selenite for two years, Se tissue concentrations in northern pike (*Esox lucius*) averaged 4.6 μg Se/g, whereas in perch (*Perca fluviatilis*) the average was 23 μg Se/g (Paulsson and Lundbergh, 1991). The perch had disappeared by the second year, but the pike had not. One explanation of the results was that perch ate invertebrates with elevated Se concentrations, whereas the pike ate water-column-feeding fish with low Se concentrations. Differences in Se exposure among predators also seem to be the case in the Bay-Delta. Fish (e.g. white sturgeon, starry flounder, and probably Sacramento splittail) that ingest benthos, and especially bivalves, have higher Se concentrations (e.g., Urquhart and Regalado, 1991) than predators that feed from the water column, like striped bass (*Morone saxatilis*) (Saiki and Palawski, 1990). Further systematic study of such hypotheses is important because it could focus attention on the species most likely to disappear first from excessive Se contamination. It is likely that the species experiencing the highest exposure of Se are at the greatest risk of extinction or to suffer population damage. It also should be remembered that biomagnification is sufficient to eliminate species at the top of the trophic structure, even when waterborne Se concentrations are in the 2 to 5 μg/L range (Lemly, 1985; 1997b; d). So some Se contaminated systems may already have lost vulnerable food web linkages. Study of systems with less extreme contamination may be one way to understand where those vulnerable linkages occur.

Existing Selenium Concentrations in Tissues of Birds and Fish in the Bay-Delta

The CDFG conducted extensive sampling of a variety of bird and fish species in the Bay-Delta between 1986 and 1990 in a *Selenium Verification Study* for the CSWRCB (White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991). The *Selenium Verification Study* was one of the most extensive surveys of Se contamination in a food web ever conducted. Fish samples from the Bay-Delta were compared to fish from Humboldt Bay (Table 12), an area with no known source of Se. The greatest differences between the two ecosystems occurred in bottom-feeding fish [e.g. English sole (*Parophrys vetulus*) with 3.05 ± 0.2 vs 1.78 ± 0.2 μg Se /g in flesh, respectively; and starry flounder with 9.2 ± 2 vs 3.6 μg Se/g in liver, respectively]. Although the sampling was limited in number, Dungeness crab from Suisun Bay contained a mean concentration of 14 μg Se/g dw tissue, compared to a mean concentration of 5 μg Se/g dw tissue in Humboldt Bay. Selenium concentrations in Pacific herring

(*Clupea pallasi*), speckled sandabs (*citharichthys stigmaeus*) and longfin smelt (*Spirinchus thaleichthys*) were not different between the two ecosystems. Uptake of Se by striped bass in the North Bay also did not appear problematic in samplings in 1986 (average, 1.3 to 1.9 μg Se/g dw) (Saiki and Palawski, 1990). Thus, some bottom-feeding fish bioaccumulated Se in excess of the reference area, but fish (e.g., herring, striped bass) that were primarily herbivorous, or fed from the water column, showed little difference in Se tissue concentrations between the two ecosystems.

The highest concentrations of Se were found in white sturgeon in the Bay-Delta (Figure 17). However, white sturgeon were not found for comparison in Humboldt Bay. White sturgeon is a long-lived benthic predator, that spends its life in the Bay-Delta, the Sacramento River, and to a small extent, the SJR (Kohlhorst et al., 1991). White sturgeon are voracious consumers of *P. amurensis*. This raises the possibility that Se trophic transfer via bivalves is a critical pathway of Se exposure in the Bay-Delta. If so, it would be expected that Se concentrations in white sturgeon should have increased after *P. amurensis* invaded the estuary in 1986. Average concentration of Se in the livers of ten white sturgeon sampled in 1986 were 9.2 ± 2.9 μg Se/g (White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991). In 1989-90, 42 white sturgeon livers were sampled; the average concentration of Se was 30 ± 21 μg/g in liver. Although variability was high (as expected for animals that move over large areas), the average Se concentration after the *P. amurensis* invasion was more than double that before the invasion.

White sturgeon were analyzed more recently in two surveys conducted to determine exposure of sport fisherman to contaminants (Davis et al., 1997; Fairey et al., 1997; San Francisco Estuary Institute, 1999). The number of white sturgeon analyzed were many fewer than determined for the *Selenium Verification Study*, and therefore the ability to detect differences or trends (the statistical power) was weak. Locations of sampling and fish size were also highly variable. From this data it is not possible to draw conclusions about Se contamination of white sturgeon in the late 1990's.

It is interesting to contrast the Se concentrations in white sturgeon to those in striped bass, another major resource species in the system. Striped bass are also anadromous fish, like white sturgeon, but they feed primarily on crustaceans from the water column**.** Contaminants in juvenile striped bass were studied in detail in 1986 by Saiki and Palawski (1990). They analyzed whole body fish samples from 22 stations from the upper SJR downstream through San Pablo Bay. Some of their observations about Se concentrations in whole-body samples of striped bass included:

- The highest Se concentrations were found in the main channel of Mud Slough and in the SJR, immediately downstream from Mud Slough.
- The mean Se concentration among the six most contaminated sites was 5.3 μg Se/g dw.
- Se concentrations were low above Mud Slough and also downstream in the SJR, as tributary dilution increased (range of 1.03 to 2.9 μg Se/g in the lower SJR, below the Merced River). So bioaccumulation was responsive to expected inputs of contamination.
- Mean Se concentrations in the North Bay were 1.3 to 1.9 μg Se/g dw. These values are at least five-fold lower than the average concentration in white sturgeon from the Bay-Delta, at that time (Table 12, when Se in flesh is converted to Se in whole-body samples).

In summary, striped bass do bioaccumulate more Se in environments where more Se is present. However, these animals are not exposed to as much Se in their food web as are sturgeon, resulting in less bioaccumulation than in white sturgeon. Striped bass are therefore less likely to be adversely affected by Se than are white sturgeon. The latter suggests links between bioaccumulation and adverse effects need to be studied, perhaps comparatively, in these species.

Eleven species of waterfowl were also analyzed in the *Selenium Verification Study* (White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991) (Figure 18). In addition to fish tissue data, bird tissue data also suggest that the most contaminated aspect of the food web is in those species that consume bivalves. Data from California reference areas (Humboldt Bay, Grays Lodge Wildlife Area, and the Sacramento National Wildlife Refuge) showed the following average Se concentrations in liver tissue: dabbling ducks, 3 to 8 μg Se/g; shorebirds, 4 to 12 μg Se/g dw, and cormorants 18 μg Se/g dw (White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991). Average concentrations in greater and lesser scaup liver were 9 μg Se/g dw and in surf scoter liver were 17 μg Se/g dw. These values are typical of uncontaminated areas elsewhere in the world, as well (Goede, 1994). Concentrations of Se in mallard (*Anas platyrhynchos*), American bittern (*Botaurus lentiginosus*), northern shoveler (*Anas clypeata*)**,** and double-crested cormorant (*Phalacrocorax auritus*) were not different between the Bay-Delta and the reference areas. Mean concentrations in two species of shorebird—willet (*Catoptrophorus semipalmatus*) and American avocet (*Recurvirostra americana*)—were about 20% higher in Bay-Delta than in reference areas. Mean Se concentrations in livers of American coot and scaup from Suisun Bay and San Pablo Bay were 2-4 times those in samples from reference areas. The highest concentrations of Se in aquatic birds in the Bay-Delta were found in surf scoter (range 13 to

368; average 134 μg Se/g range in liver) from Suisun Bay and San Pablo Bay. Annual averages from Suisun Bay ranges from 80 to 240 μg Se/g for the period 1986 to 1990. These annual averages in surf scoter liver are from 7 to 11 times those averages in samples from Humboldt Bay for the period 1986 to 1989 (annual averages, 11 to 16 μg Se/g). These concentrations also exceeded concentrations found in surf scoter from Morro Bay, the Central Bay and the South Bay (White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991). Concentrations in surf scoter livers from the North Bay were also two to three-fold higher in 1988, 1989 and 1990, than in 1986.

Concentrations of Se varied remarkably among bird species with different food preferences in San Pablo and Suisun Bay. The most contaminated birds (surf scoters) had Se concentrations in their livers that were up to two orders of magnitude higher than the Se concentrations in mallards and American bittern. Because of feeding habits, it seems that vegetarians exhibited some of the lowest Se concentrations among bird species, whereas benthic predators had the highest concentrations. More specifically, animals whose prey included bivalves were most contaminated. Surf scoter, for example, are benthic feeders whose prey include bivalves, gastropods and crustaceans, with some plants, macroalgae, insects, polychaetes and fish (Henny et al., 1995; Hoffman et al., 1998). In general, scaup obtain approximately 40% of their diet from animal food sources versus scoter who obtain approximately 95% of their diet from animal food sources.

In 74 samples from an array of studies, Skorupa and Ohlendorf (1991) reported mean concentrations in bird eggs from reference sites as 1 to 3 μg Se/g. More than 90% of values were below 3 μg Se/g. The authors concluded that concentrations above 3 μg Se/g in eggs represent contamination (Skorupa and Ohlendorf, 1991). Thus, data exist to compare Se concentrations in bird eggs in the Bay-Delta. However, only limited studies in the broader Bay-Delta ecosystem are available (e.g., Lonzarich et al., 1992; Ohlendorf and Marois, 1990).

EFFECTS OF SELENIUM ON WILDLIFE

Selenium is an essential element necessary for the formation and proper functioning of glutathione peroxidase, an important antioxidant enzyme. The window between required concentrations and toxic concentrations of this element is narrow compared to other toxins (e.g., National Research Council, 1976; Wilbur, 1983; Hodson and Hilton, 1983; Presser and Ohlendorf, 1987; SJV Drainage Program, 1990b). In excessive amounts, Se is erroneously substituted for sulfur in enzymes and the structure of the proteins is disrupted. The result is dysfunctional enzymes and proteins. Reproductive failure and/or teratogenesis (deformities in developing young) are the earliest manifestations in the organism. When eggs hatch, the developing soft tissues and hard tissues of the young are deformed, because of disrupted protein structure. In fish, teratogenesis is induced when larval fish are relying on their attached yolk sac for nourishment and development. Once external feeding begins Se will not cause further deformities in the juvenile fish. Thus the vulnerable pathway is mother to egg to developing larvae and fry.

Deformities may not always be lethal themselves, but they lower the probability that the deformed individual will survive. In fish, deformed larvae either die or quickly fall prey to predators and thus are rare in the juvenile or adult populations (Lemly, 1993c). This circumstance was evidenced in Belews Lake, North Carolina by a decreased incidence of deformities in juveniles, but not fry, when more predators were present. Thus, in assessing prevalence of teratogenic effects it is important to focus on newly emerging larvae and fry.

Community simplification (including local extinction of some species) is ultimately the result of excessive Se contamination. Sixteen of the twenty fish species that originally inhabited Belews Lake disappeared when Se contamination increased. Kesterson Reservoir was thought to contain a multi-species assemblage of warm water fish before discharges of irrigation drainage waters began (Skorupa, 1998a). Only mosquitofish (*Gambusia affinis*) persisted after Se contamination was introduced (Saiki, 1986; Saiki and Lowe, 1987; Saiki et al., 1991; Skorupa, 1998a). Hamilton (1999) recently presented the hypothesis that Se contamination of the Colorado River Basin in the 1890 to 1910 period caused the decline of native endangered fish species [particularly razorback sucker (*Xyrauchen texanus*) and Colorado pikeminnow (*Ptychocheilus lucius*)] and continues to inhibit their recovery. Hamilton (1999) cites four lines of evidence linking Se as a causative factor in simplifying this fish community:

- selenium concentrations in the Colorado River (water, invertebrates and fish) are strongly elevated as a result of irrigation drainage inputs, which began in the 1890's;
- adverse effects on the endangered species and other species have been demonstrated at the level of contamination that occurs presently;
- disappearance of large Colorado pikeminnow and razorback sucker was documented in 1910 to 1920 before disturbances (e.g., dam building) other than substantial input of irrigation drainage; and

- absence of young razorback suckers in historic collections suggest reproductive failure (lack of recruitment) was the cause of the population collapse.

Hamilton (1999) concludes that reservoir construction and introduction of exotic species have undoubtedly contributed to the decline of endangered fish species in the Colorado River, but that Se must also be included as an important contributing factor. Restoring native species in the Bay-Delta and its watershed is an important goal of the CALFED Ecosystem Restoration Plan (CALFED, 1998a; b; 1999a; b; c; d). The lessons from the Colorado River suggest that Se cannot be ignored as an issue that can inhibit accomplishment of that goal.

Selenium concentrations in food and concentrations in tissues have both been employed to evaluate how the exposure of Se experienced by an animal is linked to effects on reproduction or teratogenesis. Linkages to concentrations in food or in tissue both have the advantage that critical exposures can be determined from field data (unlike toxicity tests which require extrapolation from independent lab waters to field exposures). To determine effects in ecosystems like the Bay-Delta, Se concentrations in invertebrates can be monitored to estimate concentrations in food and critical exposure in the predator itself can be determined from concentrations in liver, flesh, or eggs.

Relating Selenium Concentrations in Food (Prey) to Effects in Predators

Fish

Concentrations of Se greater than 3 μg/g in the diet of fish result in deposition of elevated concentrations in developing eggs, particularly in the yolk. Dietary Se concentrations of 5 to 20 μg/g load eggs beyond the teratogenic threshold (Table 13 and Lemly, 1998a). Extinctions of fish species occurred in Belews Lake, when Se concentrations in invertebrates were in the concentration range of 20 to 80 μg/g dw. Concentrations in invertebrates in Kesterson National Wildlife Refuge were greater than 100 μg Se/g dw in the presence of Se-induced bird deformities and disappearance of most species of fish.

Birds

Laboratory studies have evaluated dietary concentrations of different forms of Se that affect reproduction in birds. Concentrations of 20 μg Se/g causes food avoidance, weight loss and mortality in adult males (Heinz and Fitzgerald, 1993). Effects were enhanced during cold winter weather. Selenomethionine in food at concentrations of 16 μg Se/g causes complete reproductive failure in mallards (Heinz et al., 1989). A diet of 8 μg Se/g selenomethionine compared to 1 μg Se/g fed to mallards caused a 33% reduction in hatching success and a 17% reduction in survival of ducklings; approximately 7% of the unhatched eggs had deformities (Heinz et al, 1989; Stanley et al., 1996). According to Heinz et al. (1989) the 8 ppm diet resulted in a mean decrease of 43% in the number of 6-day-old ducklings compared to controls. Most recently, Heinz (1996) concluded that the dietary threshold that results in teratogenic effects was between 4 and 8 μg Se/g dw; above 8 μg Se/g the percentage of deformities rose rapidly.

Ohlendorf (1989) reported that bird eggs generally contain 1 to 3 times the dietary Se of breeding females. Heinz et al. (1989) showed that Se in eggs of mallards (experimental exposure) was closely related to hen's dietary exposure to Se (fed selenomethionine). Average egg concentrations were 2.5 to 4.0 times dietary concentrations. However, diets supplemented with inorganic Se result in Se concentrations in eggs that are only 0.1 to 0.18 times dietary concentrations. Skorupa and Ohlendorf (1991) concluded that, if assimilation of Se in the wild is similar to Se-methionine in the laboratory, then dietary Se of 5 μg Se/g dw would yield 15 μg Se/g dw in eggs. This level in eggs was the lowest mean concentration associated with embryo teratogenesis at Kesterson Reservoir. Ohlendorf (1989) concludes that hatchability of eggs is reduced when dietary concentrationa are 6 to 9 μg Se/g. So, similar to fish, 5 to 9 μg Se/g dw in food encompasses the critical dietary thresholds in birds.

Thus, both field and laboratory studies suggest that the Se concentrations typical of bivalves in Suisun Bay and San Pablo Bay (6 to 20 μg Se/g, Table 13 and Figures 14 to 16) are beyond the threshold of Se concentrations in food that are likely to cause reproductive damage and teratogenesis in bivalve predators.

Relating Selenium Concentrations in Tissue to Effects in Predators

Fish

A number of studies have related tissue concentrations of Se in fish to teratogenic or reproductive effects (Table 14). Reproduction has the advantage of being a very sensitive endpoint to study. But, environmental factors as well as Se can affect reductions in reproductive success in nature. Short-term studies always suffer from the difficulties of separating causes of changes in reproductive success. Long-term studies can be more effective, in that environmentally-caused effects on reproductive success tend to fluctuate, whereas pollutant caused changes are more likely to be uni-directional with exposure to the pollutant. No long-term studies are available from the Bay-Delta, however. Teratogenesis is perhaps a less sensitive measure of Se effects, but has the very attractive advantage of being a more Se-specific outcome (i.e., many fewer factors cause teratogenesis than affect reproductive success). From a review of the literature, Lemly (1998b) recommended the following toxic effects thresholds from Table 14:

- whole body, 5 to 7 μg Se/g dw;
- skeletal muscle, 6 to 8 μg Se/g dw;
- liver, 15 to 20 μg Se/g dw;
- ovary and egg, 5 to 10 μg Se/g dw,
- larvae/fry, 8 to 12 μg Se/g dw.

Deformities increase rapidly in prevalence once Se in fish eggs exceeds 10 μg/g dw. High proportions of some fish populations showed deformities above 20 μg Se/g dw whole-body tissue. Reviews of field and lab studies (Table 14) show that the lower whole-body tissue threshold for effects may be between 4 and 6 μg Se/g; and it seems quite certain that teratogenesis and reproductive failure consistently begin to appear at tissue concentrations in excess of 15 μg/g dw. Only a few fish species have been studied in detail, however, and species undoubtedly vary in tolerance. Although the universality of a critical tissue level is difficult to evaluate, the values are in agreement with case studies from Belews Lake, North Carolina; Sweitzer Lake, Colorado; and lakes in Sweden (Skorupa, 1998a; b). In the Bay-Delta in 1989-90, the mean Se concentration found in 62 samples of white sturgeon muscle was 15 μg/g dw and in 42 samples of liver was 32 μg/g dw (Table 12 and Figure 17). Both means are above the levels at which deformities are likely to occur (Table 14) and some levels in individual fish (range 6 to 80 μg Se/g, liver; 2 to 50 μg Se/g, muscle) far exceed tissue thresholds for reproductive effects. However, the relation of reproduction and Se-induced teratogenesis has never been studied in white sturgeon. A limited study of white sturgeon caught in San Pablo Bay and the Sacramento River showed Se concentrations in ovaries and egg yolk components above thresholds for effects (Table 14) (Kroll and Doroshov, 1991).

Birds

Tissue thresholds in birds are not too different from those in fish. Heinz (1996) stated that the embryo is the avian life stage most sensitive to Se poisoning. Skorupa (1998 a; b; c) has concluded that Se concentrations in eggs are a good choice for a risk metric to determine avian embryonic exposure and response. Skorupa and Ohlendorf (1991) originally suggested that teratogenesis thresholds were between 13 and 24 µg Se/g dw mean egg Se. This range remains consistent with later studies (Table 15), if dry weight is assumed to be 4 to 5 times wet weight. Hatchability is more sensitive than teratogenesis; but it is more ambiguous to interpret in the field, because it is also sensitive to non-contaminant perturbation. Comparing Kesterson National Wildlife Refuge and a reference site, Ohlendorf et al. (1986) showed a strong correlation between embryonic Se exposure and embryonic viability (hatchability). Hatching failure started increasing rapidly above 10 µg Se/g dw egg. Skorupa (1998a) suggests the critical exposure concentration causing reduced hatchability, for sensitive birds, is 6 to 7 µg Se/g dw in eggs. He bases this conclusion on a variety of case studies around the world and a body of work in the Tulare Basin, California. Not all species are of equal sensitivity, of course. The predicted embryo deformity threshold for ducks is 15 to 20 µg Se/g (Skorupa, 1998 a; b; c). In black-necked stilts the critical concentration in eggs for embryo deformity is 18 to 25 µg Se/g dw, and in avocets it is 38 to 60 µg Se/g dw. In Martin Reservoir, Texas (Skorupa, 1998a), Se at 11 µg Se/g in red-winged blackbird (*Agelaius phoeniceus*) eggs was associated with 50% depression in egg hatchability, although patterns of contaminations were not as clear as in other field cases. Hepatic (liver) concentrations may be a less precise indicator of pathological conditions than are egg concentrations (Table 15). Heinz (1996) concluded that concentrations in liver greater than 10 µg Se/g wet wt (40 µg Se/g dw based on 75% moisture content) should be considered possibly harmful to the health of young and adult birds. A very high risk of embryo deformity exists when the mean Se concentration (wet weight) in the liver of a population of birds exceeds about 9 µg Se/g (36 µg Se/g dw). Reproductive impairment occurred at 3.5 µg Se/g on a wet wt basis (14 µg Se/g dw) and at 4.7 µg Se/g on a wet wt basis (18.8 µg Se/g dw) (Heinz et al., 1989; Heinz, 1996).

O'Toole and Raisbeck (1998) argue that tissue residues should be interpreted flexibly, and used mainly as an index of exposure. They suggest that it is necessary to examine all possible causes of lesions before attributing cause and effect. They also suggest that field-observed effects levels should be consistent with those experimentally induced (the basis for the thresholds).

Loss rates of Se are another important consideration for migratory waterfowl or fish. Surf scoter, greater and lesser scaup, and white sturgeon may experience high Se exposures during their residence time in the Bay-Delta, but Se concentrations may decline as the animals move to less contaminated breeding grounds. Many aspects of the reproductive effects specific to the Bay-Delta remain unstudied, especially in the species that are most threatened. Mean liver tissue concentrations of greater and lesser scaup and canvasbacks approach or exceed thresholds for adverse effects (Figure 18 and Table 15). From 1986 to 1990, individual and mean annual average Se concentrations in liver of surf scoter far exceed thresholds during their residence in Bay-Delta (Table 15). Concentrations in liver of surf scoter in the North Bay are in the range of Se concentrations in livers of ducks, coots, grebes, and stilts sampled at Kesterson Reservoir in 1983-1984 (Table 15). Hoffman et al. (1998) in a study of adult male surf scoter (n = 11) and greater scaup (n = 11) in Suisun Bay in 1989 found a mean of 67 μg Se/g dw in greater scaup and 119 μg Se/g dw in surf scoter. Surf scoter populations are also rapidly declining in North America, and they remain one of the least understood of the migratory waterfowl species (Henny et al., 1995). Selenium concentrations seem to rise extraordinarily in scoter in response to Se exposures. Henny et al. (1995) have suggested that caution should be exercised in linking tissue concentrations to effects in animals with strong bioaccumulative capabililties. For example, in other ecosystems bottle-nosed dolphins (*Tursiops truncates*), Risso's dolphins (*Grampus griseus*), and cormorants seem to bioaccumulate high concentrations of Se compared to other species. Mineral granules rich in Se are common in these species (Nigro and Leonzio, 1996). It could be speculated that some species concentrate Se in non-toxic forms, and, in such species, thresholds for adverse effects may be higher than in other species. This hypothesis remains untested, but points to the great need to better understand the links between internal Se exposure and effects of Se across a range of species. Those species exposed to elevated Se concentrations as a result of their dietary choices should be of special interest in such studies.

There is currently no data proving that white sturgeon, surf scoter, or greater and lesser scaup are suffering from Se toxicity in the Bay-Delta because of the difficulties associated with studies of migratory fauna. Data from both food exposures and tissue residues strongly indicate that these animals are at or near significant risk. Despite the complexities, planning an effective restoration of the Bay-Delta ecosystem depends on studies of the effects of Se on reproduction, population biology, and life histories of migratory waterfowl and anadromous fish that are such important components of the Bay-Delta ecosystem.

Comparison to Selenium Hazard Index

Lemly (1995; 1996a; b) defined hazard as a toxic threat to birds and fish that can be characterized by Se concentrations in the environment (water, sediment) and exposure of fish and birds to that hazard (tissues). His systematic approach can be applied to data compiled for the Bay-Delta from 1986 to 1996.

Lemly defined five categories of hazard:

- *High Hazard*: Imminent, persistent threat sufficient to cause complete reproductive failure in most species of birds and fish.
- *Moderate Hazard*: Persistent toxic threat sufficient to substantially impair, but not eliminate reproductive success. Some species will be severely affected; others will not be affected.
- *Low Hazard*: Periodic or ephemeral toxic threat that could marginally affect reproductive success of some sensitive species, but most species will be unaffected.
- *Minimal hazard*: No toxic threat identified but concentrations of Se are slightly elevated as compared to uncontaminated reference sites.
- *No hazard*: Se concentrations are not elevated in any ecosystem component compared to reference sites (Lemly, 1995; 1996a).

Lemly developed a scoring method which assigned points to define Se hazard in specific systems: no hazard = 5; minimal hazard = 6 to 8; low hazard = 9 to 11; moderate hazard = 12 to15; high hazard = 16 to 25 (Lemly, 1995; 1996a). The scores represented summation for the lines of evidence (i.e., samplings of water, sediment, invertebrates, fish eggs and bird eggs). The aggregate rather than the average was chosen as the best representation of hazard because any route, alone, can cause toxicity.

We can further define three levels of certainty of the statement of hazard:

- The greatest certainty occurs if waterborne, particulate, bioaccumulation, and predator lines of evidence are accompanied by direct observations of teratogenesis or reproductive impairment. A strong level of certainty is possible if data are available from all links in the chain of processes, but no observations of reproductive impairment are available.
- Moderate certainty results if more than one line of evidence from a chain of evidence are available.
- Low certainty is chosen if the hazard evaluation is based upon one line of evidence.

Table 16 shows the results of the hazard analysis from several ecosystems (Lemly, 1985; 1995; 1996a; 1997c; Kroll and Doroshov, 1991) compared to conditions in the Bay-Delta using data gathered in from 1986 to 1996. This table comparing hazard ratings from different ecosystems illustrates the diversity of conditions that can occur in ecosystems receiving Se discharges. Most notably, high dissolved Se concentrations in some rivers (e.g., LaPlata, Mancos, Animas Rivers in Colorado, New Mexico, and Utah, respectively) can be accompanied by low concentrations in sediments. Invertebrates are moderately contaminated in some of those systems and not in others. Nevertheless, moderate to high contamination was noted in fish eggs. Obviously, Se cycling, Se speciation, as well as form and concentration in suspension are not sufficiently known from many of the surveys to identify the factors critical to determining Se hazard. In all the reservoirs and pond environments surveyed by Lemly (1995; 1996a;b; 1997a; b; c), elevated dissolved Se concentrations are accompanied by Se contamination in sediments, substantial contamination of invertebrates and a high hazard to fish and bird eggs. Lemly (1997c) suggested that long retention times in reservoirs contributed to the contamination of all media and the high hazard. He suggested that as residence times increased, the potential increased for Se to be bioaccumulated, to be deposited in and recycled from sediment, and to adversely affect fish and birds. For hazard evaluations Lemly (1995; 1996a) suggested that sampled nesting birds should be those feeding locally. He suggested coots, grebes and dabbling ducks as good choices. Suggested choices of fish for hazard evaluation included minnows, sunfish (centrarchids), suckers, catfish, and trout. Our studies of Bay-Delta suggest these species are not the most sensitive because their exposure to Se is less than that of species that feed on bivalves. In the Bay-Delta, the best choices are benthivores based on feeding habits of species at risk.

Suisun Bay seems to be typical of a system with high residence time subjected to Se contamination. Using data from the above analysis, a ranking of Suisun Bay under the conditions of 1990-96 is possible using Lemly's scheme. The results of the aquatic hazard assessment and hazard rating for the Bay-Delta for the period 1990 to 1996 (Table 16) are:

Total score = 17   Hazard = High

Direct observation of reproductive processes in the most sensitive predators is not possible in the Bay-Delta because the most contaminated species are migratory. This lack of data adds some uncertainty to the hazard rating. Nevertheless, the certainty, as defined previously, is high. Selenium data were available from water, particulate material, bioaccumulation in invertebrates, and predator bioaccumulation (in the latter case, more than one species). Further, toxicity threshold/extinction information, in general, can be related to the Se data for both birds and fish. So the high hazard rating can be made with relatively high certainty. It is possible that the hazard level declined after 1998, when refinery discharges declined. Studies underway may help determine further site-specific ratings.

If an out-of-valley solution to the Se problem results in carefully managed discharges of Se to the Bay-Delta via the SJR (for example at 7,000 lbs per year), the forecast suggest the resulting hazard could be high. Selenium from the SJV replaces, in terms of food web exposure and effects, the Se removed in refinery cleanup. If an SLD is constructed and it discharges during low flow seasons, a high hazard seems a certainty, and the risk of loss of fish and bird species will be substantial. Alternative engineering solutions (in-valley and out-of-valley) will undoubtedly be proposed. Each should be analyzed using the scheme above at its appropriate time scale in relevant detail.

FORECASTS

A major goal of this report is to illustrate a systematic approach or mechanism for conducting forecasts of Se effects on prey (food) and predators. Several feasible future conditions are used to develop examples of forecasts. The choices of conditions are not nearly as important as the process of evaluating those choices. However, the results of the chosen forecasts themselves provide guidance to help narrow the range of possible management alternatives.

The approach can be used with any set of explicitly stated conditions. From each set of assumed conditions we:

- calculate or forecast loads, volumes, and concentrations;
- define speciation and transformation;
- model bioaccumulation in generic bivalves and
- predict tissue residue-based effects on predators.

Forecasts of Composite Input Loads and Volumes to the Bay-Delta

As noted previously, the protocol for linking Se load and Se concentration under assigned hydraulic conditions and time duration is:

composite freshwater endmember concentration = composite input load/composite input volume

Four major inputs make up a composite input load: agricultural drainage via direct discharge to the Bay-Delta, effluents from the North Bay refineries, SJR inflows, and Sacramento River inflows. The composite input volume in the Bay-Delta is most affected by inflows from the Sacramento River and SJR (Figures 9 and 10). We will constrain each of the inputs and volumes to a given set of conditions as we construct feasible forecasts for Se loads to the Bay-Delta.

The projections or outputs of the model are presented by season, where a season is defined as six months of predominantly high river inflows (December through May) or six months of predominantly low river inflows (June through November). Seasonal presentation (high flow season versus low flow season) is the least complicated approach to account for riverine influences which are very different in different seasons. Flows are also variable on time scales shorter than season. To illustrate the effects of these shorter time scale changes, (and to further illustrate the methodology), several forecasts for Se concentrations were determined from monthly loadings. Riverine influences also depend upon water year type. In combination with flow seasons, we forecast for a critically dry year and a wet year.

A wide range of agricultural Se input loads are possible, depending upon which management strategies are chosen, as described earlier (also see Appendices A and B). Several factors influence agricultural loads of Se that would be delivered directly to Bay-Delta:

- choice of drainage conveyance, either the SJR or an extension of the SLD;
- demand for drainage from agriculture or the Se load targeted by environmental safeguards;
- hydraulic discharge in the SJR or the SLD;
- selenium concentration in the SJR or the SLD or the load conveyed by the SJR or SLD; and
- proportion of the conveyance discharge that reaches the Bay-Delta.

Potential ranges of annual input loads were derived earlier (Tables 6 and 7) assuming Se discharge was continuous and are presented here as discharged load per six months (i.e. one-half the annual load under a constant rate of loading). We will constrain our forecasts to selected scenarios within the three general ranges of SJV loadings described earlier (Tables 8 and 9).

1. *Pre-targeted loads conveyed by the SJR* (3,400 or 3,590 lbs Se discharged in six months). The value we will use for the targeted loads will be toward the maximum projected by the TMDL/TMML process: 6,547 lbs per year or 3,274 lbs in six months. We will assume this load is delivered via the SJR with full conveyance to the Bay-Delta (no recycling of the SJR). A SJR inflow of 0.5 MAF is assumed during the low flow season of both wet and dry years. During the high flow season of a wet year, we assume 1.1 MAF is allowed to enter the Bay-Delta.

2. *SJR as a de facto drain* (range of 381 to 15,300 lbs in six months). If the TMDL/TMML process resulted in management of a constant concentration of Se in the SJR year-around, a different load would result than if management is based upon load. The Se load delivered to the Bay would also depend upon how much of the load is passed through the Delta. Little is presently known about water movement within and through the Delta; a value for transport (i.e., percent of SJR that reaches the Bay-Delta) is necessary but it should be recognized as hypothetical. Effects of Se on the SJR ecosystem are not included in our analysis. Examples of Se loads that could be transported via the SJR are given below (also see examples in Table 9).
    - *Load is managed at the USEPA criterion of 5 μg Se/L in a wet year*. If an annual discharge of 3 MAF for the SJR at Vernalis is assumed and it is assumed that 75% of that reaches the Bay-Delta, then an annual Se load of 30,600 lbs is expected (15,300 lbs Se in six months).
    - *Load is managed at the USFWS proposed criterion of 2 μg Se/L in a wet year*. In this case an annual load of 12,240 lbs of Se is released to the Bay if annual flow is 3 MAF and 75% of it passes through the Delta (6,120 lbs in six months).
    - *Dry years*. If annual discharge from the SJR is 1.1 MAF and 25% reaches the Bay-Delta, as might be expected in below normal precipitation, then the annual Se loading would be 9,262 lbs from the SJR at the 5 μg Se/L criterion and 3,705 lbs at the 2 μg Se/L criterion (1,852 or 4,631 lbs Se in six months).
    - *Restored ecosystem*. Load is managed at a constant 0.5 μg Se/L with 75% of the annual SJR flow and load delivered to the Bay-Delta during the high flow season and 25% allowed to enter in the low flow season. A concentration of 0.5 μg/L is lower than both the USEPA criterion (5 μg Se/L) and the USFWS proposed criterion (2 μg Se/L). In this case an annual load of 4,080 lbs is conveyed by the SJR assuming a flow of 3 MAF in a wet year. In a dry year, annual SJR flow of 1.1 MAF, the annual load is 1,496 lbs Se. This type of forecast will be typified in a scenario that considers restoration of the SJR during proposed increases in flow of the river to aid fish passage. (381, 1,020, 1,115, or 3,060 lbs in six months).
3. *Demand-driven loads with management of drainage quantity and quality in an extension of the SLD*. For our specific calculations of SLD effects, we will assume that a) demand for drainage

is met by construction of an extension of the SLD which discharges directly to the Bay-Delta; b) the SLD extension delivers either 0.05 MAF each six months (half design flow capacity of existing SLD, 150 cfs) or 0.11 MAF each six months (full design flow capacity of SLD, 300 cfs); and c) Se concentrations in the SLD will vary with the success of treatment. Specific forecasts are:

- *Demand-driven loads with priority given to management of quality and quantity* (6,800 or 18,700 lbs Se discharged in six months). We will calculate one forecast using a condition of 150 cfs in the SLD (0.05 MAF of drainage or half capacity) with a Se concentration of 50 μg/L. Under this condition, 6,800 lbs Se would be discharged in six months. We assume, in a second forecast, that 62.5 μg Se/L drainage is discharged at full capacity (0.11 MAF); the loading would be 18,700 lbs Se discharged in six months. These two loads bracket the lowest end of the range of cumulative potential loadings from the different subareas (or combinations of subareas) of the SJV (Tables 5 through 7).
- *Demand-driven loads with low priority given to management of quality and quantity* (44,880 and 89,760 lbs Se in six months). We will calculate two forecasts for this condition. Minimal treatment could result in direct (unblended) discharge of existing shallow ground water and no control on the quantity of discharge. Thus, this forecast employs 150 μg/L Se concentrations in the SLD with the drain running at full capacity (0.11 MAF in six months) (44,880 lbs Se discharged in six months). The second case will assume 300 μg Se/L and 0.11 MAF of discharge in six months (89,760 lbs Se discharged in six months), assuming little regional management (as described earlier). These two loads bracket potential loadings from a valley-wide system draining most potential problem lands, with minimal management (Tables 6 through 8).

In order to calculate the total Se load to the Bay-Delta, and the resulting Se concentrations, climate, oil refinery loads, SJR recycling, and Sacramento River condition are included in the forecasts as follows:

1. As noted previously, the magnitude and fate of the Se loads are highly dependent upon climatic regime. Climate scenarios are derived from existing data.

- *Critically dry year*. Eight critically dry years have occurred in the Bay-Delta watershed between 1978 and 1998, so this is an important condition to consider. The data for this calculation were taken from 1994.
- *Wet year*. We used data from 1997, a wet year by the California DWR definition.

2. We will assume in all forecasts that oil refineries meet the 1998 permit requirements of approximately 1,360 lbs Se per year or 680 lbs per six months (Table 10).
3. In demand-driven load forecasts during dry years, we assume that Se loadings from the SJR are very low. The forecasts implicitly assume that use of the SLD could relieve the pressure for discharge of drainage in the SJR. The forecasts also assume continued substantial recycling of the SJR, so only 500 to 1,000 AF of SJR water with a concentration of 1 to 2 μg Se/L reaches the Bay-Delta in dry years during high or low flow seasons (3-5 lbs Se in six months).
4. During wet years in periods of high flow, less recycling of the SJR occurs, with substantially more SJR throughput to the Bay-Delta. To accurately reflect this condition in demand-driven load forecasts, we assume 2 MAF of SJR inflow reaches the Bay-Delta. We assign a concentration of 1 μg Se/L for this inflow (5,440 lbs Se in six months)**.**
5. Loadings from the Sacramento River will be determined at 0.04 μg/L Se times the hydraulic discharge.

Table 17 shows the inputs to the Bay-Delta, the climatic scenarios (water year and season), and the range of Se loadings that will result from the above conditions. The loadings in Table 17 will be employed in the modeling of bioaccumulation and prediction of effects on predators. Specific cases will be highlighted in summary tables that follow. The examples are not exhaustive in their coverage of all conditions; but the choices bracket the wide range of loads possible in the future from SJV acreage that is in need of drainage (Tables 8 and 9, and Appendix B).

Forecasts of Waterborne Selenium Concentrations

<u>Calculating composite selenium input (or freshwater endmember) concentrations</u>

Ultimately, Se concentrations in the Bay-Delta will be determined by the sum of all Se loads from different sources, the choice of conveyance to the Bay-Delta, and the sum of all freshwater inflows as influenced by climate and management. To forecast concentration ranges for Se in the estuary under different scenarios, the model assumes all Se inputs are confined to a single location at the head of the estuary. Then it is assumed that the composite Se input is diluted through the estuary, as freshwaters move toward the sea (Figure 11). We will represent Se concentrations by values for composite freshwater concentrations expected at the head of the estuary (i.e., landward value) and by the concentration expected at half the value of seawater [approximately 17.5 psu (practical-salinity units)] (i.e., seaward value) based on the salinity gradient. The chosen seaward location is similar to salinities that occur at Carquinez Strait (i.e., the narrow waterway between Suisun Bay and San Pablo Bay in the North Bay) during low flow seasons. It should be remembered that hydrodynamic models (e.g., Cheng et al., 1993; Monsen, 2000; Burau and Monismith, in preparation) are necessary to forecast the spatial detail under simulated physical SLD discharge conditions. Development of such models for Se is feasible and should be a high priority in future evaluations of effects of a SLD extension directly discharging to the Bay-Delta. In lieu of regionally specific models, a simple mixing model approach provides a useful first order estimate of mean regional Se concentrations.

Comparing forecasted selenium concentrations to observed conditions prior to refinery cleanup

To initially test the validity of the approach, an average composite freshwater endmember Se concentration was calculated for conditions resembling those that were documented in Suisun Bay prior to refinery cleanup (Tables 2 and 18). Forecasts are for a high flow season during a wet year; and for a low flow season during both a wet and dry year, similar to conditions selected for projections of future conditions. The Sacramento River flow for six months of high flow was taken from 1997 data (17 MAF). The Sacramento River inflow during six months of low flow in 1997 and 1994, respectively, provide two other cases (i.e., 2.3 MAF and 1.62 MAF). SJR inflows were 3 MAF for high flow inputs in 1997 and 0.1 MAF in the latter two low flow cases. Refinery discharges are in the range (2,040 lbs in six months) measured before refinery cleanup (average 1986-1992, 2,505 lbs per six months) (CSFBRWQCB, 1992a; b; 1993; Cutter and San Diego-McGlone, 1990) and no SLD discharge is included.

The calculated average composite freshwater concentration of Se during six months of high flow in a wet year is shown in Table 18. The forecast concentration is 0.22 μg Se/L, using a mean concentration of Se in the Sacramento River of 0.04 μg/L Se and in the SJR of 1 μg Se/L. This is comparable to the Se concentration of 0.16 μg Se/L determined after high flows in April 1986 (Cutter, 1989). The contrasting influences of the SJR and the Sacramento River are interesting to note in this example. Concentrations of Se in the SJR are much higher than concentrations in the Sacramento

River (1 μg Se/L vs. 0.04 μg Se/L, respectively). The load of Se from the SJR is also substantial compared to the load from the Sacramento River (2,992 lbs vs. 925 lbs Se per six months, respectively). Concentrations of Se are as low as 0.22 μg Se/L at the head of the estuary because of dilution by the high volume of low-Se water from the Sacramento River. A Se concentration of 0.11 μg/L is projected at our selected seaward location of Carquinez Strait.

The concentration of Se at 17.5 psu (i.e., approximate location of Carquinez Strait) during the six months of low flow in a wet year is projected as 0.20 μg Se/L; in a critically dry year it is 0.27 μg Se/L (Table 18). Selenium concentration is highest during periods of low flows, because dilution from the Sacramento River is reduced in years of low rainfall. The concentration forecasts are remarkably close to the range of values found within the estuary by Cutter (1989) (0.15 to 0.44 μg/L Se). The correspondence of these calculations with observed data confirms that the basic foundation of the forecasts is reasonable.

Forecasting influence of a San Luis Drain extension: seasonal waterborne selenium concentrations

Five specific forecasts were constructed to evaluate impacts on the Bay-Delta from direct discharge of an extension of the SLD (Tables 19 through 21). Those forecasts are calculated for the three different climatic conditions and feasible loadings described earlier.

1. *6,800 lbs Se discharged in six months* if management of drainage quality and quantity were a high priority (half-capacity or 150 cfs of drain water with a Se concentration of 50 μg/L). In the three different climate regimes (Tables 19 through 21), the six-month average Se concentration at the head of the estuary during the low flow season would range from 1.21 μg Se/L in a wet year (Table 20) to 2.07 μg Se/L during a critically dry year (Table 21). In the high flow season of a wet year, six months at this load would result in an average composite freshwater concentration of 0.28 μg Se/L (Table 19).
2. *18,700 lbs Se discharged in six months* if the SLD operated at full capacity, carrying drain water with a Se concentration similar to that in the Grassland Bypass Channel Project (i.e., 62.5 μg/L). This forecast is one of the more likely demand-driven loadings in the long-term if successful treatment technology is applied to drainage and the amount of *problem land* is that considered by the SJV Drainage Program (Table 6). In the three different climate regimes, concentrations at the head of the estuary during the low flow season of a wet year would

average 2.99 μg Se/L and would average 5.07 μg Se/L over six months of low flow in a critically dry. Concentrations would average 0.51 μg Se/L at the head of the estuary during the six months of high flow in a wet year.

3. *44,880 lbs Se discharged in six months* if drainage contained 150 μg/L Se, and the drain operated at full capacity. This loading would provide for drainage from *problem lands* without investment in management of the drainage (e.g., direct discharge of shallow ground water). Even during high flow, Se concentrations would exceed 1 μg Se/L (i.e., 1.02 μg Se/L) at the head of the estuary under these conditions. During low flow six-month average concentrations would always exceed the USEPA criterion no matter what the rainfall (6.97 to 11.87 μg Se/L).
4. *89,760 lbs Se discharged in six months* if the most severely salinated soils supplied a drain at full capacity and no treatment technology was available. This scenario is not highly likely given expected emphasis on source control and treatment. However, if it should occur, extremely high Se concentrations would be found in the estuary under low flow conditions (13.8 to 23.5 μg Se/L) (Tables 19 through 21). Average concentration at the estuary (1.9 μg Se/g) would approximately equal the USFWS recommended criterion (2 μg Se/L), even during the high flow season (Table 21).

<u>*Forecasting influence of selenium release via the San Joaquin River: seasonal waterborne selenium concentrations*</u>

1. *Regulating load*. This scenario assumes Se load is targeted for regulatory or environmental purposes at 7,000 lb Se per year load limit and 3,500 lbs Se discharged in six months. Conveyance is fully via the SJR. The projected range of Se concentrations in the freshwater endmember for the Bay-Delta during the low flow season scenarios is 0.57 to 0.86 μg/L Se; concentrations would be 0.28 to 0.43 μg/L at Carquinez Strait (Tables 20 and 21). These values are slightly enriched from the conditions that applied before refinery cleanup (0.39 to 0.53 μg/L Se at the head of the estuary and 0.20 to 0.27 μg/L at Carquinez Strait) (Table 18). So, in terms of total Se concentrations, this load of Se from the SJV would replace the Se removed by investment in refinery waste treatment. During a six-month high flow season during a wet year if 3,500 lbs of Se were discharged (Table 19), concentrations would be two-fold lower (0.12 μg Se/L at the head of the estuary and 0.06 μg Se/L at Carquinez Strait) than

conditions prior to refinery cleanup (0.22 μg Se/L at the head of the estuary and 0.11 μg Se/L at Carquinez Strait, Table 18).

2. *Regulating concentrations in the SJR: a restoration forecast*. Environmental restoration is often vaguely defined. A specific "restoration" scenario for the SJR might place explicit limits on Se concentrations in the river and emphasize increasing SJR inflows (less recycling of the SJR) to the Bay-Delta to aid fish movement in certain seasons of the water year (CALFED, 1998a; b; 1999a; b; c; d; EA Engineering, Science, and Technology, 1999). Managing concentration in the SJR contrasts to previous scenarios in which Se load was managed. In calculating the effect of such "restoration" on Se concentrations in the Bay-Delta, the concentration assigned in the "restoration" scenario is 0.5 μg/L for the SJR at Vernalis. It should be noted that this concentration has not been achieved in the recent past (Table 5), and we are not suggesting that the technology is available to achieve it or that it would be easy to achieve by management decree. This is a specific condition, done for illustrative purposes. Conditions and Se loads for the restoration scenario include:
   - no SLD input;
   - constrain concentrations in the SJR at Vernalis to 0.5 μg Se/L;
   - convey 75% of the annual SJR flow and load to the Bay-Delta in the high flow season and 25% in the low flow season;
   - assume the SJR inflow for a wet year is 3 MAF annual flow and a dry year is 1.1 MAF;
   - control industrial inputs to meet the July 1998 mandate of approximately 1,400 lbs Se per year;
   - vary Sacramento River inputs with flows as they do now (i.e., 0.04 μg Se/L at 19.3 MAF annual inflow in a wet year and 0.04 μg Se/L at 6.6 MAF annual inflow in a dry year).

   Under the "restoration" scenario in the high flow season of wet or dry years, the composite freshwater Se concentration is 0.11 to 0.15 μg Se/L for a wet year and a dry year, respectively. In the low flow season of a wet year, the composite freshwater Se concentration is 0.23 μg Se/L. In the low flow season of a dry year, the composite freshwater Se concentration is a similar 0.24 μg Se/L. These Se concentrations would be less than those that occurred prior to refinery cleanup (compare Tables 18 and 22). An improvement also is achieved over the targeted load scenario (compare Tables 19, 20, 21, and 22). Conditions would be most improved, compared to before refinery cleanup, during the “bottleneck” period of low flow seasons in both wet and dry years. Less increase in concentration occurs in the Bay-Delta during low flow seasons in the “restoration” scenario because inputs of Se decline as flows decline. In high flow seasons inputs of Se increase, but the increase in dilution due to the higher inflows of the Sacramento River offsets the higher loads from the SJR and concentrations in the Bay-Delta decline.

3. *Regulating selenium concentrations in the SJR: effect of high flows and consequent high loads as a result of expanded selenium objectives*. The advantage of discharging an increased Se load during high flows under the concentration management scenario does have some limits in the low flow season and if Se concentrations in the SJR increase. The concentration objective at which the SJR is held constant by implementation of a management plan is increased in a series of scenarios illustrated in Figure 19. If the Se concentration in the SJR inflow is a constant 1 μg/L using the same conditions as defined above, the concentration at the head of the estuary is 0.36 μg/L during a wet year in the low flow season. During a dry year in the low flow season, the concentration is comparable at 0.32 μg Se/L. However, if the concentration is a constant 2 μg/L, the concentration at the head of the estuary is 0.60 μg/L during a wet year in the low flow season, as compared to 0.46 μg/L Se during a dry year in the low flow season. In this case, the low flow season of a wet year is more at risk from higher concentrations than the low flow period of a dry year. This occurs because the higher Se load during the wet year is not offset as much by increased flows as occurs seasonally.

Monthly waterborne selenium concentrations

The six-month scenarios described above represent average seasonal Se concentrations (i.e., low flow season versus high flow season). Six-month averaged forecasts could be misleading, however, because flows are variable over shorter time scales. To illustrate the effects of these shorter time scale changes, and to further illustrate the methodology, Se concentrations were forecast that would result from monthly loadings. The forecasts are based on wet year flows (1997). The results of the monthly forecasts are presented graphically in Figures 20 and 21 and supplemental data are given in Appendix F, Tables F1 and F2. The forecast conditions are:

1. *Operation of the SLD at full capacity (0.2 MAF) conveying drainage at quality levels typical of the present re-use of the drain by Grassland subarea (62.5 μg Se/L).* The annual load of Se from the SLD would be 36,720 lbs (or approximately 18,700 X 2 = 37,400 lbs, Table 17). Although SLD monthly inputs are constant (3,060 lbs per month) in this scenario, Se concentrations at the head of the estuary increase progressively from 0.24 μg Se/L in January to 4.5 μg Se/L in October (Figure 20). The range of concentration change is dramatic, because dilution declines through the year as river inflows decline. The peak concentration in October would be a permanent feature of monthly variability in Se concentrations as long as a constant load is released from the drain throughout the year (Figure 20). The vulnerability of the estuary to adverse effects is generally greatest during the seasons of lower flows (June through November), but a detailed monthly analysis shows that vulnerability is at a maximum in the fall months when water exports most exceed river inflows (Figures 9 and 10). Figure 20 expresses this scenario as a function of both input load and composite freshwater endmember Se concentration. Figure 21 shows the composite freshwater endmember concentration at both the head of the estuary and at Carquinez Strait for comparison.
2. *Management of the SJR at 2 μg Se/L with full conveyance to the Bay-Delta during a wet year (6.06 MAF).* It is also instructive to evaluate the variation in monthly concentrations that might develop at the head of the estuary as a result of managing a constant SJR input concentration. The annual load of Se discharged to the Bay-Delta from the SJR in this forecast is very similar to that discharged by the SLD in the above scenario (32,936 lbs vs. 36,720 lbs for the SLD scenario above, Table 17). The highest loads (approximately 10,400 lbs each month) are discharged in January and February. The highest Se concentration at the landward reach is 1.2 μg/L (Appendix F, Table F1). Two periods of maximum concentration occur, in March through June and in September through November (Figure 20). The latter period of elevated concentration coincides with that under constant discharge from the SLD (Figure 20). Concentrations in the Bay-Delta are much lower from April through December if the SJR is the conveyance vehicle than if the SLD is the conveyance. This disparity in loading is because monthly loads from the SJR decline as hydraulic discharges decline and most of the load is released with the highest flows. Weighting with flow prevents the extreme concentrations that build-up as a result of high loads during periods of low inflow if load is constant. The fall build-up in Se concentration illustrates an important problem with releasing Se via an artificial

conveyance facility. Additional limitations also exist when high loads are released during high flows (see Figure 19 and later discussion).

3. *Management of the SJR at 1 μg Se/L with full conveyance to the Bay-Delta during a wet year*. The annual load discharged in this condition would be 16,468 lbs in a high flow year. The monthly trends are the same as those under the 2 μg/L Se scenario, but the amplitude of the fall peak is reduced (Figure 20). The highest concentrations in the landward reach of the estuary are 0.60 and 0.68 μg Se/L in September and October (Appendix F, Table F2), respectively (about 1.5 times the maximum observed before refinery cleanup, Table 18). Concentrations near Carquinez Strait in October (Figure 21) are about equal to the highest concentrations (0.30 to 0.34 μg Se/L) observed prior to refinery cleanup based on as seasonal analysis (Table 18), although speciation would probably be different (see later discussion).

Summary of forecasts

In general, a summary of the forecasts for the SLD conveyance and SJR targeted load scenarios (Table 23; Figures 22 and 23) shows that the most vulnerable years are critically dry years. The low flow season is the critical period of each year for the Bay-Delta. However, if concentration in the SJR is regulated under a constant concentration management plan and SJR inflows are increased, wet years are more vulnerable than dry years, but only during the low flow season (Figure 19).

Specifically, Figure 23 is a graphical tool that forecasts waterborne Se concentrations that would result from a wide range of six-month hydraulic discharges (emphasizing lower flow regimes), and a wide range of Se loads. Each line illustrates a Se concentration that would result from the different combinations of these variables. From this figure, the composite freshwater endmember concentration of Se (i.e. that concentration at the head of the estuary) can be estimated from any combination of climate (as indicated by differing total river inflows) and Se load. The strong dependence of Se contamination on weather and water demand (which, together, determine discharge to the estuary) is evident. Figure 23 illustrates the extreme vulnerability of the estuary to Se inputs during low flow seasons (cumulative discharges of 1 to 2 MAF over six months). For example, for total input loads of approximately 7,700, 20,000 and 46,000 lbs Se at defined cumulative volumes of 1.3 and 2.3 MAF during low flow seasons, the range of estuary Se concentrations would be from 1.2 to 12 μg Se/L.

Using the range of loading forecasts employed previously, selenium concentrations in the Bay-Delta will increase under all scenarios that include a SLD extension, and especially as the flow capacity of the SLD is achieved and/or if concentrations of Se increase in the discharge (Table 23 and Figure 22). A minimum estimate of loads from a SLD extension is 6,800 lbs in six months (or 13,600 lbs annually). This scenario can only be achieved if the drain is managed at a flow of 150 cfs and the most optimistic treatment technologies are invoked. Even under this scenario, composite freshwater endmember Se concentrations would increase two to four-fold over concentrations typical prior to refinery cleanup (see also Table 18). Freshwater endmember Se concentrations in the driest of years could exceed the 2 μg Se/L toward the head of the estuary.

If a SLD extension is built to the Bay-Delta, pressure may be strong to maximize its potential to carry salt-laden waters. Under this condition, loads from the SLD may approach the level of 18,700 lbs in six months (37,400 lbs per year). Under this load scenario, average Se concentrations in the Bay-Delta at the head of the estuary for the six-month low flow season of a wet or dry year are forecast to exceed the USFWS recommended criterion of 2 μg Se/L through all of Suisun Bay (Table 23 and Figure 22). This exceedance would also occur at Carquinez Stait during the low flow period of dry years.

If treatment technologies are not developed or if demand becomes more important than load management, then the quality of discharged drainage could drop. If, on average, drainage quality becomes similar to that of subsurface drainage (≥150 μg Se/L) rather than blended drainage in the western SJV, and that is combined with full flow in the SLD, then extreme concentrations would occur in the Bay-Delta. Under a forecast load of 44,880 lbs Se in six months**,** Se concentrations of >6.97 μg Se/L at Carquinez Strait are projected during the low flow season of both wet and dry years.

A concentration of 1 μg Se/L is three times higher than presently found in the Bay-Delta in a normal rainfall year (Cutter 1989; Cutter and San Diego-McGlone, 1990; and CSWRCB, 1992a; b; also see Table 18) and represents the Canadian quality guideline (Environment Canada/Health Canada, 1995; Outridge et al., 1999). This Se concentration cannot be achieved near the Carquinez Strait in the low flow season by any scenario that includes an extension of the SLD, except a load of 6,800 lbs per six months (Figure 22). In the high flow season of a wet year, concentrations forecasts at the Carquinez Strait are 0.14 to 0.94 μg Se/L.

An important component of the monthly analysis (not evident in the six month analyses) is the very high Se concentrations that result each year in the fall. The strong dependence of Se contamination on weather and water demand, which, together, determine discharge to the estuary, is also evident.

Concentrations in excess of 2 μg Se/L would extend through much of Suisun Bay and San Pablo Bay in the SLD forecast. It is possible that the dilution assumptions employed here might understate the geographic extent of Se distributions in projections for October. Sophisticated physical models are being developed for Suisun Bay and could be very helpful in describing such important details (Monsen, 2000; Burau and Monismith, in preparation).

Forecasts of Speciation and Transformation

Speciation of Se in the Bay-Delta is controlled by physicochemical processes and speciation in the sources of input (Cutter, 1989). Speciation will change as sources change in importance. Prior to 1998, refinery inputs of selenite were a principal influence on speciation and bioavailability. Refinery inputs declined in July 1998. A lower proportion of the total Se was selenite in the late 1990's than in the 1980's (Cutter et al., in preparation). It is likely that the proportion of selenate in inputs would increase if a SLD extension were used to convey irrigation drainage to the Bay-Delta or if/when SJR inflows to the Bay-Delta increase. As we forecast, biotransformation to Se(-II) and/or sediment accumulation and recycling of Se(-II) in the Bay-Delta are highly likely under increased SJR loading if the transformation conditions prevalent at present in the Bay-Delta are operable on the SJR discharge. This influx of Se(-II) could be accentuated if marshes are restored in areas subjected to inflows from the SJR or a SLD extension.

As discussed previously, speciation is a critical consideration in estimating ecological effects of Se. Speciation drives the transformation reactions that determine particulate Se concentrations and forms. Bioaccumulation from particulates is the primary route by which Se enters the food web, so the reactions that determine particulate concentrations are critical to eventual trophic transfer. Trophic transfer determines food web exposures and effects on predators.

Ultimately, forecasts of Se speciation should be derived from biogeochemical, kinetic speciation models (Bowie et al., 1996). This type of model is not yet ready for application to the Bay-Delta, although the completion of its development should be a high priority. In the absence of a model, speciation is included in our analysis by forecasting based upon mixes of species that have been observed in nature under circumstances possible for the Bay-Delta. We will then forecast how each mix of species would affect transformations of dissolved Se to particulate Se (i.e. speciation is implicit in our choice of transformation reactions).

Transformation will be quantitatively expressed by the distribution of Se between particulate and dissolved forms, the Kd (see previous discussion). The effect of speciation and transformation will be incorporated by using Kd's observed in previous studies (Table 11) to project a ratio to total Se typical of a given speciation regime. For each combination of Kd and speciation, we will also incorporate the form of particulate Se observed under those circumstances at other locations (Table 11) to enable a projection of overall bioavailability.

Defining speciation, transformation, and bioavailability

Three sets of speciation regimes and Kd's in which we assume a specific distribution of Se among particulate forms are presented below. These speciation and biochemical behavior patterns will be used throughout the forecasting of concentrations of Se in particulates, bivalves, and predators.

- ***High Bioavailability***

  Speciation: *high proportion of selenite plus organo-Se (≥ 60%)*

  Kd: *1 X 10^4* (C1)

  Precedent: *estuarine suspended material in the Bay-Delta*

  Particulate bioavailability: *60% high and 40% moderate*

  To bound a high bioavailability scenario, we assume that Se(IV) and at least part of the Se(-II) contribute to biotransformation to organo-Se. Preliminary studies in the late 1990's showed that as much as 60% of dissolved Se was Se(IV) plus Se(-II) in Suisun Bay. Selenite has declined since the refineries reduced their inputs, but organo-Se has become a larger proportion of the dissolved Se (Cutter et al., in preparation). In Suisun Bay, this speciation regime is accompanied by a particle/dissolved distribution (Kd) of ≥ 10^4. For example, distribution coefficients for estuarine suspended material in most of the Bay-Delta were 8.2 X 10^3 to 2.1 X 10^4, between September 1986 and October 1996. Biotransformation may explain these high Kd's. Some species of diatoms, the most common phytoplankton in the North Bay, have Kd's higher than 10^4 in laboratory experiments. For bioavailability calculations, we will assumed the form of the particulate Se under these conditions is 60% biotransformed Se and 40% oxidized material of moderate bioavailability. Biologically, this Kd is most relevant to water column-feeding species of consumer organisms, like filter-feeders.

- ***Moderate Bioavailability***

  Speciation: *low proportion of biotransformable (Se(IV) or bioavailable Se(-II)) (< 30%)*

<u>Kd</u>: 3 X 10^3 (C2)

<u>Precedent</u>: typical of shallow water estuarine sediments or marine waters

<u>Particulate bioavailability</u>: 60% moderate and 40% high

If sources of Se change, it is possible that the proportion of Se as Se(IV) + Se(-II) in the Bay-Delta will decline to less than 60%. Even if the proportion of Se(IV) and Se(-II) remains high, it is possible that the bioavailability of Se(-II) is less than Se(IV). To account for either of these possibilities we will assume 30% of total Se contributes to biotransformation at the rate of Se(IV). A speciation regime of 30% biotransformable Se and 70% less reactive Se is similar to that often observed in undisturbed marine waters, and so it is a scenario with some precedent. Shallow water estuarine sediments also show a distribution coefficient of 3 X 10^3 to 1 X 10^4 (Table 9**,** Velinsky and Cutter, 1991; Cutter et al., in preparation). Again, this Kd coincides with a mixed speciation regime [60% Se(VI) and 40% Se(IV) plus Se(-II)]. We will also assume that this speciation and Kd combination results in particulate Se that is 60% in a form of moderate bioavailability [detrital Se(-II) or particulate Se(IV) + (VI)]; and 40% in a form of high bioavailability (biotransformed organo-Se). Biologically, this scenario applies to biota that predominantly ingest sediments with concentrations diluted by non-transformed load.

- ***<u>Low Bioavailability</u>***

  <u>Speciation: p</u>redominantly Se(VI)

  <u>Kd</u>: 1 X 10^3 (C3)

  <u>Precedent:</u> Systems like the area of a wetland near the input site of selenate-dominated irrigation drainage waters

  <u>Particulate bioavailability</u>: 50% low, 40% moderate, and 10% high

  This scenario assumes that most of the Se entering the Bay-Delta remains as Se(VI). Selenate is transformed, but the Kd's of selenate-dominated waters are typically lower than where a higher proportion of the species are organo-Se. Circumstances exist, such as near the irrigation inflows of Benton Lake, Montana, where Kd's are approximately 10^3 (Zhang and Moore, 1996). This value is also at the lowest end of the partitioning constant range characterizing Bay-Delta sediments and is probably the most optimistic scenario that can be hoped for, in terms of generating particulate Se and ultimately biological effects. For forecasting bioavailability, we will assume this material is 50% slurry-generated Se(0) of relatively low bioavailability, 40% oxidized material of moderate bioavailability, and 10% organo-Se of high bioavailability. This scenario would apply most readily to deposit feeding benthos, especially those feeding within sediments.

In general, we recognize that the Kd-concept used above has limitations and that there are uncertainties about future speciation should a SLD extension begin discharging Se loads to the Bay-Delta. Nevertheless, the three speciation/transformation regimes described above are quite likely to fully bound the possibilities. Using them we can forecast at least the ranges of particulate Se concentrations and particulate forms.

Comparison to Bay-Delta conditions prior to refinery cleanup

It is instructive to visually compare projections from the Kd's to existing data for the Bay-Delta. In Figure 24, suspended particulate Se concentrations (Cutter et al., in preparation) are plotted against dissolved concentrations. Lines describing predicted particulate concentrations using Kd's of 1×10^3 and 1×10^4 are superimposed on the plots. A Kd of 1×10^3 (C3) is too low to describe any of the existing suspended sediment data making it a low probability forecast. The October 1996 data (the highest concentrations observed in any survey) exceed 1×10^4 (C1) and the September 1996 data fall between the two values. In Figure 25, similar data are presented in a different way. Particulate concentrations are forecast from dissolved concentrations that occurred landward to seaward in the Bay-Delta in October 1996. The different Kd's described above forecast three different trend lines for particulate concentrations through the estuary. The October 1996 particulate data is superimposed upon these projections. The superimposed data illustrate that a Kd of 1×10^4 (C1) is the best choice for this data set. A Kd between 3×10^3 (C2) and 1×10^4 (C1) would best fit the September 1996 data if it were plotted similarly. The three Kd's used for the forecasts were, of course, developed based upon empirical observations. So it is not surprising that direct comparison to data from the Bay-Delta are consistent with the choices.

Forecasts of Particulate Selenium Concentrations

Sediment quality guidelines

As discussed previously, the principal risk of sediment to fish and birds is via the aquatic food chain. Sediment guidelines are based on sediment concentrations as predictors of adverse effects through the food chain. Proposed sediment quality guidelines for Se (μg Se/g in particulate material or sediment) provide a context to evaluate forecast particulate Se concentrations:

- *no effect concentration: <1 to 2.0 μg Se/g.* Concentrations lower than this value produce no discernible adverse effects on fish and wildlife and are typical of background concentrations in uncontaminated environments (Skorupa, 1998b).
- *threshold for effects and the level of concern for Se in sediment: 2 to 4 μg Se/g.* Concentrations in this range are elevated 10 to 20 times above typical background concentrations (Engberg et al., 1998; Skorupa, 1998b).
- *site-specific for Suisun Bay, potential for increase in adverse effects: >1.5 μg Se/g.* Concentrations in this range may produce discernible adverse effects in some circumstances (Luoma et al., 1992), whereas Engberg et al. (1998) and Skorupa (1998b) suggest such levels rarely produce discernable adverse effects in freshwater environments.
- *observed effect concentration: 4.0 μg Se/g* (Canton and Van Derveer (1997).
- *toxicity threshold* of > 4 μg Se/g. Concentrations in excess of this value have a high certainty of producing toxicologic and reproductive effects (Engberg et al., 1998).

Skorupa (1998b) provided a compilation of background and biotic effects levels as part of the U.S. Department of the Interior's National Irrigation Water Quality Program. Canton and Van Derveer's (1997) conclusions about sediment-based criteria are based upon less data and a relatively insensitive community analysis (Hamilton and Lemly, 1999).

Particulate selenium concentrations (all concentrations are in μg Se/g dry weight, dw)

Tables F3 to F5 in Appendix F show detailed data for four load scenarios under three different climate regimes should Se be released directly to Suisun Bay via a SLD extension (also see Tables 19 through 21 for composite freshwater endmember concentrations). Transformation constants typical of suspended sediments (C1), shallow water bed-sediments (C2), and low reactivity conditions (C3) are employed in each set of calculations. Table 24 summarizes particulate Se concentrations under these four load forecasts using a proposed SLD extension, a targeted load scenario using the SJR, and under a "restoration" scenario for the SJR. Forecasts are compared to data reflective of conditions prior to refinery cleanup. Sediment quality guidelines for Se are also shown.

The forecasts using the SLD for conveyance show that during a low flow season in a critically dry year (Table 24):

- all releases to the Bay-Delta via a SLD extension under the three assumed Kds (C1, C2, and C3) result in particulate concentrations >2.0 μg Se/g at the head of the estuary.
- only under the lowest SLD extension discharge assumption (6,800 lbs in six months) combined with the lowest Kd (least likely, C3), would a particulate Se value be observed (2.07 μg Se/g) below the *observed effects concentration* of 4.0 μg Se/g. In all other cases the certainty of effects would be elevated.
- if the Kd of suspended material were that observed in all existing studies of the Bay-Delta (C2), projected loads of Se from a SLD extension would result in particulate Se concentrations in upper Suisun Bay of 6.2 to 35.6 μg Se/g. The certainty of effects would be high to very high.

Under all but the most optimistic transformation scenarios, forecast loads with management of quantity and quality of 6,800 to 18,700 lbs per six months would yield particulate Se concentrations in the upper estuary that would exceed 4.0 μg Se/g. Selenium concentrations of 5 to 119 μg Se/g are possible if management is not a priority.

A low flow season in a wet year would yield particulate Se concentrations that are approximately 60% of those forecast for a dry year (Table 24):

- if a load of 6,800 lbs were discharged in six months via a SLD extension, the forecast range of most likely concentrations (C1 – C2) is 4 to12 μg Se/g (rounded off).
- if the SLD was managed at full flow capacity and with Se concentrations like those in the Grassland Bypass Channel Project (18,700 lbs in six months), particulate concentrations of 9 to 30 μg Se/g are forecast under C1 and C2 conditions. The latter concentration is >7X higher than the level at which toxicologic and reproductive effects are highly likely (Engberg et al, 1998).
- Under a C3 transformation, only SLD loads in the range of the lowest loading scenario for the SLD (6,800 lbs in six months) would result in particulate Se concentrations of <1.5 μg/g.

If monthly forecasts are considered, values in the late fall months would be considerably higher than these six-month averages [compare waterborne Se data trends presented on a monthly basis (Figures 20 and 21; Appendix F, Tables F1 and F2)].

Releases of a SLD discharge in the Bay-Delta during the high flow season of a wet year result in exceedances of the observed effects level under all assumed SLD discharges only if Kd's of 1 X 10^4 (C1**,** typical of suspended sediment) characterize transformations (Table 24). However, it should be recognized that the forecast concentrations are averages over the six-month high flow period. Flows are very variable during this period, so the actual period of lower concentrations will probably be shorter than six months. This is also the time period when particulates from the SLD extension are most likely to add to the Se load in the estuary.

The forecast for the targeted load (3,500 lbs per six months) using the SJR for conveyance shows that (Table 24):

- During a low flow season, the targeted load approach could result in particulate concentrations in excess of 4.0 μg Se/g if transformations are typical of suspended sediment (C1), but not if shallow sediment-type transformations prevailed (C2).
- During the high flow season of a wet year, particulate Se concentrations remain below 1.5 μg Se/g for all three transformations considered.

The forecast for the "restoration" scenario in the SJR shows that (Table 24):

- During the high flow season of a wet year, particulate Se concentrations for the "restoration" scenario are similar to those that would occur during the targeted load scenario (i.e., below 1.5 μg Se/g).
- During the low flow season in a critically dry year or a wet year, particulate Se concentrations are less than those that would occur during a targeted load scenario and remain below 2.5 μg/g.

All SLD discharge scenarios predict particulate Se concentrations greater than those forecast for prior to refinery cleanup (Table 24). Particulate Se concentrations lower than those modeled prior to refinery cleanup are predicted to occur:

- in the "restoration" scenario for the SJR in all modeled water year types and seasons; and
- in the SJR targeted load scenario during the high flow season of a wet year.

Cumulative summary

A cumulative summary of Se loads and concentrations is given in Table 25. Composite freshwater endmember and particulate Se concentrations at the head of the estuary are shown for an agricultural load input of 18,700 lbs released during six months via a SLD extension or of approximately 3,500 lbs released during six months via the SJR (see Tables 19 through 21 for composite loads). The forecasts for prior to refinery cleanup are given for comparison. The forecasts highlight the importance of reactivity in determining particulate concentrations. Clearly, benefit would come from knowing these dissolved/particulate transformations with more certainty for the Bay-Delta. For each composite freshwater endmember Se input, we illustrate three assumed alternative particulate transformations [low reactivity (C3), shallow sediment (C2), and suspended sediment (C1)].

For the SLD scenario of 18,700 lbs per six months (Table 25), it is notable that exceedance of the USEPA waterborne criterion of 5 μg Se/L (low flow season of a dry year) is always accompanied by exceedance of the proposed observed effect particulate criterion (4.0 μg Se/g), no matter what the reactivity of the Se. Also under this load scenario, the USFWS proposed waterborne criterion of 2.0 μg Se/L is exceeded in the composite freshwater endmember concentration for the low flow season of a wet year. At a composite freshwater endmember Se concentration of 2.0 μg Se/L, particulate Se concentrations might exceed the lowest proposed no effect concentration (1.5 μg Se/g), but not the observed effect level. However, a typical estuarine Kd (C2) would result in particulate Se concentrations of >4 μg Se/g. Even during high inflows, the observed effect guideline is exceeded if a Kd typical of October 1996 occurs (C1).

For the SJR targeted load scenario of 3,500 lbs per six months (Table 25), composite freshwater endmember Se concentrations remain below 1 μg Se/L. However, particulate Se concentrations only remain below 1.5 μg/g at low reactivities (C3) or during the high flow season of a wet year. During low flow seasons of both wet and dry years, particulate Se concentrations exceed 1.5 μg/g, and in cases of high reactivity (C1) could exceed 4 μg Se/g.

In summary, loadings, inflows, and biogeochemical transformation rates are critical to determining particulate Se concentrations and thus important determinants of the ecological effects of a discharge conveyed directly to the Bay-Delta. Most feasible SLD discharges result in concentrations of particulate Se during low inflow periods that are above the threshold of toxicity based upon the only available estimates of *no effect* and *observed effect* particulate Se guidelines. This is especially true if the transformation conditions prevalent at present in the Bay-Delta (C1 and C2) are operable on a proposed discharge from an extension of the SLD. All forecast particulate Se concentrations exceed those forecast for conditions prior to refinery cleanup, except under the targeted load SJR scenario during the high flow period of a wet year. The “restoration” scenario for the SJR results in forecast particulate Se concentrations that are lower than those forecast for the Bay-Delta prior to refinery cleanup.

Other possible scenarios

- *No reaction of Se(VI).* If inputs of Se from agricultural drainage increase, it is possible that the predominant dissolved form in that discharge will be Se(VI). On a purely geochemical basis, it might be asserted that dissolved Se(VI) will not be reactive in the Bay-Delta ecosystem. This minimal reactivity would require that dissimilatory reduction to sedimentary Se(0) not occur in sediments or wetlands, no adsorption because of competition with sulfate, and no selenate uptake by primary producers. Biotransformation of Se is, indeed, minimized in at least some flowing water (lentic or river/stream) systems, compared to wetlands. However, there is no precedent in nature for a complete absence of Se biotransformation to particulate concentrations. At least a Kd of 0.5 X 10^3 is usually seen, especially if residence times are sufficient. Thus, the argument of minimal reactivity is extremely unlikely as inflows recede seasonally, during low inflow years, and in wetlands and shallow water environments of the system.
- *Direct SLD discharge of suspended particulate Se from an extension of the SLD.* Input of suspended particulate material containing elevated concentrations of Se is likely from a SLD extension directly into the Bay-Delta. The SLD during its operation from 1981 to 1985 acted as a partial treatment facility by removing Se from agricultural drainage and sequestering it in sediment and biotic material that had settled in the bottom of the drain (Presser and Piper, 1998). Sediments that are highly contaminated with Se have accumulated in the SLD to date and are likely to continue to accumulate during its renewed use by the Grassland subarea to convey drainage to the SJR (Appendix E, Tables E1 and E2). Selenium concentrations in SLD sediment have exceeded the hazardous Se waste criterion for solids (100 μg Se/g, wet weight) at times in the past and almost all concentrations are above that designated as a toxic threshold in sediment for biotic effects (> 4 μg/g) (Engberg et al., 1998). Re-suspension and at least some transport of those sediments during elevated flows seems a reasonable forecast should the SLD be extended to the Bay-Delta. For example, the SLD was briefly re-opened in early 1995 to relieve flooding in the western SJV and acted as a conduit for discharges into Mud Slough and the SJR (Presser and Piper, 1998). Transport and dilution of such particles probably cannot

be estimated with any reasonable certainty. The discharged particulate Se would probably originate as primarily Se(0), but oxidation would also occur with longer residence times in suspension or in the water column. Source material also may include algal mat that may contain organic-Se [i.e., bioavailable Se(-II)]. The following forecast of direct discharge of suspended particulate Se from a SLD extension is instructive, but speculative. It illustrates how even small inputs of the existing contaminated SLD sediments could affect the Bay-Delta.

- o If the SLD inflow is 5% of the flow of river inputs to the Bay-Delta and suspended material concentrations are similar in both the Sacramento River and the SLD (based on relative flows in a wet year at low flow).
- o If average particulate Se concentration in the SLD particles is 100 μg Se/g and particulate Se in the Sacramento inflows is 0.2 μg Se/g.
- o Then 5% of the particles in the Bay-Delta at the confluence of the two will be SLD particles and the Se concentrations in the particle mixture will be:
  [(0.05 X 100 μg Se/g) + (0.95 X 0.2 μg Se/g)] = 5.19 μg Se/g from direct particulate input.
- o During a critically dry year particulate Se concentrations would be twice this value.
- o Particulate Se transformed from the dissolved inputs from the SLD would add to these concentrations, therefore our estimate is conservative in this respect.

- *Local hotspots*. The Se concentration estimates discussed above represents broad scale average concentrations that would result from mixing. This approach does not allow determining the spatial details of distributions. More sophisticated hydrodynamic models would be necessary to provide such detail (Burau and Monismith, in preparation). However, hotspots of particulate Se contamination could develop in an ecosystem subjected to direct SLD discharges. Most notably, wetlands close to a SLD-extension discharge would be likely to accumulate high concentrations of Se.

Forecasts of Bioaccumulation in Consumer Organisms

Calculating bioaccumulation in a generic bivalve (modeling)

Table 26 shows the range of biological values employed in the *DynBaM* model for bivalves in the Bay-Delta. The model is for a generic bivalve (i.e., physiological constants are averages over a small range from several bivalve species, Reinfelder et al., 1997; Lee et al., in preparation). Calculations specific to *P. amurensis* and *C. fluminea* also could be conducted. Some data for these species are recently available. The common parameters for a generic bivalve used in the model are as follows:

1. Ingestion rate (or feeding rate) of 0.25 gram food/gram tissue dw per day (estimate for many bivalves based on review of literature in Luoma et al., 1992).
2. Efflux rates (or rate constant of loss) of 0.02 per day (average of 0.01 - 0.03 per day).
3. Assimilation efficiencies (AE) approximately 20% (low bioavailability) to 80% (high bioavailability) as a function of particle type (see below).

Combining the above factors and the range of particle transformations that affect bioavailability (Table 26), bivalve bioaccumualtion will be cast in terms of assimilation efficiencies (AE in percent):

- *Inefficient transformation: Kd = 1 X 10^{3}.* The particulate forms are 50% Se(0) of relatively low bioavailability, 40% oxidized material of moderate bioavailability, and 10% organo-Se of high bioavailability. The AE derived from this mixture is 35%:

  AE1 (0.23 X 50%) + (0.4 X 40%) + (0.79 X 10%) = 35%

- *Shallow water estuarine sediments: Kd = 3 X 10^{3}.* The particulate form are 60% of moderate bioavailability [detrital Se(-II) or particulate Se(IV) + (VI)]; and 40% in a form of high bioavailability (biotransformed organo-Se). The AE derived from this mixture is 56%:

  AE2 (0.40 X 60%) + (0.79 X 40%) = 56%

- *Estuarine suspended material*: *Kd = 1 X 10^{4}.* The particulate forms include 60% biotransformed Se of high bioavailability and 40% oxidized material of moderate bioavailability. The AE from this material (presumably by an estuarine filter-feeder, Table 26) would be 63%, derived as:

  AE3 (0.79 X 60%) + (0.40 X 40%) = 63%.

- *Estuarine suspended material – purely biogenic:* A fourth AE (79%) is also included to take into account the possibility that all suspended particulate Se in the estuary would derive from biogenic transformation to Se(-II).

  AE4 (0.79 X 100%) = 79%.

- To complete the range of considered AEs, a fifth AE is derived for all particulate material being of a form of low bioavailability, Se(0). The AE derived is 23%:

  For range (0.23 X 100%) = 23%

Comparing model predictions to Bay-Delta conditions prior to refinery cleanup

Generic bivalve data (Table 26) were employed to forecast bioaccumulation of Se for a range of concentrations using two extremes of AE, 80% (all biotransformed) and 20% (all elemental Se) (Table 27). The purpose of this calculation was to verify that the model bracketed reasonable predictions of Se bioaccumulation. The range of particulate Se concentrations used in the calculation spanned the concentrations of Se determined in surveys of the brackish Bay-Delta (0.5 to 3.0 μg Se/g dw) and at the head of the Bay-Delta (0.5 to 8.0 μg Se/g dw). Three observations from the forecasts of Bay-Delta conditions prior to refinery cleanup are of interest:

- The forecast concentrations of bioaccumulated Se span the exact range of Se concentrations found in bivalves in this system (Figures 15 and 16; Tables 13 through 15). Thus, the independently derived physiological constants, when used with environmental values collected through field studies, bound bioaccumulation with reasonable accuracy (results similar to those reported by Luoma et al., 1992 and Wang et al., 1996).
- A four-fold difference in bioaccumulation would be expected if the particulate form of Se changed. At the same concentration of particulate Se, bivalves would bioaccumulate four-times more Se from the biotransformed particulate Se than from elemental Se. Although this bioaccumulation is significant, the effect is relatively small compared to the effects of changing the mass of Se in the load.
- The field validation results verify that the model will be useful in forecasting the range of consumer organism bioaccumulation under different input scenarios for Se.

Bivalves as food for predators

The most sensitive response of ecosystems to Se occurs in higher trophic level predators (e.g., birds and fish) (Ohlendorf, 1989; Hamilton et al., 1990; Lemly, 1996b; c; Skorupa, 1998a; Hamilton et al., 2000a; b). Effects on predators (see reviews in Lemly, 1998b; Skorupa, 1998a; Hamilton et al., 2000b) have been defined based on:

- Se concentrations in their food
- effects on predators themselves expressed as Se residues in tissue.

Bivalves (clams) are an important food source for the predators of interest in the present evaluation (Luoma et al., 1992). So one type of guideline for bivalve tissues should be based upon their use as a food source for fish and birds. Guidelines for predators based on food are (see also Tables 13 through 15):

- *10 μg Se/g in food = Threshold of effects on predators*. Concentrations in predator food (invertebrate tissues) above 10 μg Se/g dw have been conclusively implicated in adverse effects on reproduction in predators (Saiki, 1986; Hodson and Hilton, 1983; Johns et al., 1988; Coyle, et al., 1993; Lemly, 1985, 1993a; c; 1997b; Hamilton et al., 1990; 2000b; Adams et al., 1998; Linville and Luoma, in press). Many studies suggest effects begin at lower concentrations, but 10 μg Se/g can be considered the value of least uncertainty. When invertebrate tissues exceed 10 μg Se/g dw the expectation is strong that adverse reproductive effects are occurring in sensitive upper trophic level species such as birds and fish.
- *15-20 μg Se/g in food = Observed conditions that coincide with extinction of some fish species.* This is the annual maximum concentration of Se in *P. amuren*sis observed between 1995 and 1996 near Carquinez Strait in Suisun Bay (Table 13; Figures 14 through 17)
- *40 μg Se/g in food = Extinction of numerous fish species*. In field studies, all but the most tolerant populations of fish species have been eliminated when Se concentrations in invertebrates reach 40 to 100 μg Se/g (Lemly, 1985; 1993a; 1997c; Saiki, 1986; Saiki and Lowe, 1987). So we might define values > 40 μg Se/g dw as invertebrate tissue Se concentrations where risks of extinction of multiple fish species are high. These are also the concentrations in prey at which less sensitive predator species show teratogenic effects (e.g. coots in Kesterson Reservoir) (Presser and Ohlendorf, 1987; Skorupa, 1998a).
- *100 μg Se/g in food = Widespread invertebrate toxicity*. Although large-scale invertebrate toxicity is probably not the most sensitive response to Se, it could be an additional outcome of extreme Se contamination. Very rarely are invertebrates found in ecosystems when Se concentrations in invertebrates are greater than 150 μg Se/g (Lemly, 1993a; 1997c; Saiki and Lowe, 1987). For the sake of discussion, we will assume 100 μg Se/g to be the level of outright, broad scale invertebrate toxicity.

<u>Generic bivalve selenium concentrations (i.e., contamination of prey)</u>

Forecast Se loads, freshwater endmember Se concentrations, particulate Se concentrations, and generic bivalve Se concentrations are shown at three different Kd's (transformation constants) and four different AE’s (generic bivalve assimilation efficiencies) in Appendix F, Tables F6 to F9. Table 28 summarizes these projected concentrations of Se in particulate material and in generic bivalve tissue as a function of four combinations of Kd’s and AE’s (C1/AE4, C1/AE4, C2/AE2, C3/AE1). Forecasts are for three loading scenarios (6,800, 18,700 and 44,880 lbs per six months) for a SLD extension release and for a SJR discharge of a targeted load of 3,500 lbs Se per six months under three different climate regimes. Also included for comparison is a forecast of Bay-Delta conditions prior to refinery cleanup.

The forecasts show that, contamination of prey would be sufficient to cause widespread extinction of fish species (> 40 µg Se/g in food) during the low flow season of any year, but especially in dry years (Table 28), if Se transformation occurs at a Kd of 3 X 10^3 or higher and:

- the proposed SLD extension discharges at 300 cfs, even if management succeeds in holding concentrations to 62.5 µg Se/L (44,880 to 18,700 lbs per six months). Some of these scenarios could also cause widespread elimination of invertebrates in addition to predicted effects on predators (> 100 µg Se/g in food).
- the proposed SLD extension discharges at 150 cfs (half capacity) and with a drainage concentration of 50 µg Se/L (6,800 lbs per six months) and the highest reactivity of suspended sediment (C1/AE3 or C1/AE4**)** occurs.
- sub-extinction threats to reproduction of birds and fish (concentrations between 10 and 40 µg Se/g dw in food) would result In low flow seasons from discharges of 6,800 lbs per six months via a SLD extension.

For loading of 3,500 lbs per six months via the SJR, sub-extinct threats exist during the low flow season of a dry year at typical shallow-water bed sediments (C2) reactivity and during the low flow season of a wet year at the highest reactivity assumed (C1).

Concentrations less than 10 µg Se/g dw in food invertebrates (i.e., the threshold of effects of predators) are found only if (Table 28):

- in the low flow season of both wet and dry years, the proposed SLD discharge is 150 cfs (half the capacity) and the drainage is treated to attain a concentration of 50 µg Se/L (6,800 lbs per six months) and if Se transformation values or reactivity is low (C3/AE1).
- in the low flow season of both wet and dry years, the SJR discharges 3,500 lbs per six months and if Se transformation values or reactivity is the lowest found in any of the receiving waters studied previously (C3/AE1).

- in wet years, if discharges of 6,800 lbs via a SLD extension or 3,500 lbs via the SJR per six months are released during high flows and reactivities are that of bed sediment or lower (C2 and C3). At the lower load, a higher reactivity (C1/AE3 or C1/AE4) also result in prey of < 10 μg Se/g, but not at 6,800 lbs Se.

In general, SLD discharges that would meet demands for drainage pose risks to fish and bird reproduction and the risk of fish extinction via contamination of their invertebrate food (Table 28). If biogeochemical conditions like those today in the Bay-Delta predominate during projected discharges, low flow periods would be a time of extreme risk for fish and bird species, especially those that include filter-feeding bivalves among their prey. Some low flow conditions include forecasts where extreme risks might be somewhat reduced. Most of those conditions are of low likelihood (reactivities that result in a Kd of $\leq 10^3$) in that such low Kd's are not typical of the Bay-Delta. Similarly, the targeted load scenario for the SJR results in prey containing < 10 μg Se/g only if reactivities are low (C3/AE1) during low flow seasons. At other reactivities (C2/AE2, C1/AE3 or C1/AE4) during low flow seasons, concentrations in prey approach (i.e., 8.7 μg Se/g) or exceed 10 μg Se/g (12 to 38 μg Se/g).

Loadings of Se from 6,800 to 18,700 lbs per six months, if released during the highest flows only, would result in exceedances of the effects levels only if the highest Kd's, of 1×10^4 (C1) were observed (i.e., if the particulate Se turns out to be as reactive as observed during longer residence times than usually occurs at high inflows). Thus, releases during high flows carry less risk for fish extinctions. However, it is important that releases during high flows be studied carefully before it is concluded that they lower risks. The fate of Se that enters the Bay-Delta estuary during high inflows is not fully known. For example, it is not known how much is retained and reacts during subsequent low flow periods or how much is transported to the South Bay during high flows and subsequently retained (Conomos et al., 1979; 1985; Nichols et al., 1986; Peterson et al., 1989). Also during high inflows, highly contaminated particulate material from either the SJR or the SLD is most likely to add to the Se load in the estuary (although, at present, suspended particulates are not typically highly contaminated during high inflows).

For comparison, forecasts of conditions in the Bay-Delta prior to refinery cleanup show exceedances of the 40 μg Se/g threshold during the low flow season of a dry year at high reactivity (C3/AE4) and of the 10 μg Se/g threshold at bed sediment reactivity (C2/AE2). During the low flow season of a wet year, 10 μg Se/g is exceeded at a high reactivity (C1/AE3 and C1/AE4). Even during high flows in wet years, this high reactivity produces prey with concentrations greater than 10 μg Se/g.

Effects on predators based on selenium concentrations in food

We take two forecasts, one for a SLD extension load of 18,700 lbs Se per six months and one for a SJR targeted load of approximately 3,500 lbs per six months, forward to link uptake by bivalves and effects on predators (Table 29). Forecasts are shown for three climate seasons and for three transformations previously selected (C1/AE3, C2/AE2, and C3/AE1). This cumulative summary also shows the composite freshwater endmember Se concentrations and particulate Se concentrations at the head of the estuary for these scenarios. The forecast invertebrate Se bioaccumulation is compared to the guidelines for effects on fish and birds from contaminated food. In this case we assume clams constitute that food.

The projection for the SLD scenario (18,700 lbs Se per six months**)** shows that (Table 29):

- Composite freshwater endmember Se concentrations in the Bay-Delta would reach the USEPA criterion of 5 μg Se/L, on average, during a dry year and the low flow seasons. At the level of the guideline, effects on fish (predator) populations from contaminated food (9-266 μg Se/g dw) would be expected, no matter what the reactivity of the Se (i.e., concentrations posing a serious risk would be reached under all feasible biogeochemical conditions).
- Composite freshwater endmember Se concentrations would fall between the USEPA guideline and the USFWS proposed criterion of 2 μg Se/L in the dry season of a wet year. If Se is of the lowest possible reactivity, bioaccumulation would not reach the 10 μg Se/g dw food guideline under these conditions. A typical estuarine Kd would result in exceedance of the 40 μg Se/g dw guideline and threaten an array of fish and birds with extinction from the estuary. So, in the most likely circumstances (those with precedent in the estuary) significant risk exists.
- Even during high inflows, effects on predators are expected if a Kd typical of October 1996 (C2) occurs. So risk is reduced, but risk of harm (to fish and birds) is not eliminated during this period.

In summary, under a loading scenario of 18,700 lbs Se per six months**,** SLD discharges usually result in waterborne and particulate Se concentrations that exceed biotic effects thresholds and concentrations of Se in bivalve prey of fish and birds that exceed dietary guidelines (10-40 μg Se/g) during the six months or more of each year when river inflows are reduced. This condition is the most likely if the transformation prevalent at present in the Bay-Delta is operable in the future. Biogeochemical transformation rates and AE's are critical determinants of the degree of contamination of the food of predators in the Bay-Delta and need to be better understood.

The projection for the SJR scenario (approximately 3,500 lbs Se per six months**)** shows that:

- Under the most likely biogeochemical conditions (Kd = 3 X 10^3, C2) risks to predators are greatly reduced compared to SLD discharge scenarios. Invertebrate concentrations of Se would fall just within the 10 to 40 μg Se/g dw range of elevated risk to reproduction in critically dry years under the most likely reactivity scenarios. Risk at this or lower reactivity would be reduced in intensity compared to prior to refinery cleanup, based upon contamination of bivalve prey.
- Contamination of food would be sufficient to suggest risk of fish extinctions (> 40 μg Se/g dw) or at the high end of the range defining risks to reproduction, if Kd's were like those often observed for suspended material in the Bay-Delta (C1), in the low flow season.

The forecasts show that the risk of conditions that are ecologically inconsistent with restoration cannot be eliminated, even under this most carefully managed condition.

Forecast of Selenium Concentrations in Tissues of Predators

<u>Choice of predators</u>

White sturgeon, surf scoter, and scaup (greater and lesser) were chosen to forecast Se concentrations in predator tissue that would result from different Se loads to the estuary. There are three reasons for this choice:

- These are the species for which the most data is available for the Bay-Delta (i.e., the *Selenium Verification Study*: White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991), and these data remain the best available data on predators.
- These are the upper trophic level species that bioaccumulate the most Se, and thus seem to receive the highest internal exposure. Changes in Se exposures in the Bay-Delta food web should have the greatest effect on concentrations of Se in these species.
- The fish and birds with the greatest Se bioaccumulation in the Bay-Delta are also likely to be the most at risk for adverse effects. Observations from other systems show that fish with the

highest bioaccumulated concentrations of Se are the first to disappear from contaminated reservoirs (Lemly, 1995; 1996a).

<u>*Relation of selenium concentrations in bivalves to selenium concentrations in predators*</u>

As discussed previously, pharmacokinetic models are the optimal approach for forecasting how changes in Se concentration or form might affect bioaccumulation by predators. Unfortunately, such models are not available for predators relevant to the Bay-Delta. An alternative approach is to statistically link predator bioaccumulation to bioaccumulation by prey (food). Urquhart and Regalado (1991) determined Se in white sturgeon, surf scoter, greater scaup, and lesser scaup at a number of times and locations when they or others also determined Se in bivalves. The bivalve *Corbicula fluminea* was collected from 1987 to 1990 in Suisun Bay (Urquhart and Regalado, 1991). Johns et al. (1988) collected *C. fluminea* from Suisun Bay in 1986. The bivalve *Mya arenaria* was collected from Humboldt Bay and from San Pablo Bay in 1988 (Urquhart and Regalado, 1991). *Potamocorbula amurensis* invaded North Bay initially in 1986, and by the late 1980's was established as the dominant bivalve in the ecosystem. No data for Se concentrations in *P. amurensis* were collected until 1995; but 1995 through 1996 average Se concentrations in this species might be used to estimate concentrations in 1990.

We have assumed that the bivalves listed above were a major food source for surf scoter, scaup, and white sturgeon during the period 1986 to 1990. The bivalve *C. fluminea* was collected during the *Selenium Verification Study* from 1987 to 1990 from Suisun Bay (White et al., 1987; 1988; 1989; Urquhart and Regalado, 1991). Johns et al. (1988) collected *C. fluminea* from Suisun Bay in 1986. The *Selenium Verification Study* collected the bivalve *Mya arenaria* from Humboldt Bay and from San Pablo Bay in 1988. Figures 26 through 28 show relations between bivalve Se concentrations and Se in the livers and flesh of these predators. Each data point represents data from a common year and common location (Table 30). Mean Se concentrations in the liver and flesh of white sturgeon, surf scoter, greater scaup, and lesser scaup are significantly and strongly correlated with mean Se concentrations in bivalves If data for *P. amurensis* is employed to match the predator data in 1990, the correlation remains strong. The 1990 concentrations in *C. fluminea* are not as strongly correlated as other years with the predators, but *P. amurensis* was the predominant benthos in 1990 in both San Pablo Bay and Suisun Bay.

The regressions in Tables 30 and 31 were employed to forecast Se concentrations in predators under the different conditions of loading and climate season employed previously. In Table 30, the mean bivalve Se concentration was matched to the mean tissue Se concentration for white sturgeon, surf scoter, greater scaup, and lesser scaup. Table 31 represents a further regression of the data. In this regression the mean for each year of data for the North Bay or Humboldt Bay for all bivalves is regressed for a specific predator. It is recognized that the uncertainty in this calculation is substantial because we are extrapolating linearly from the small set of data available. Nevertheless, the calculation adds an important and highly relevant perspective to the forecasts presented earlier. Once these concentrations are forecast they can be compared to toxicity thresholds known for the tissue Se concentrations in birds and fish. This line of evidence is a second demonstration, in addition to concentrations in food, of how Se might affect predators in the system.

Selenium concentrations in predators

Table 32 shows forecasts of hepatic (liver) concentrations of Se in white sturgeon, surf scoter, greater scaup, and lesser scaup that result from regression with forecast bioaccumulation by bivalves, in two possible Se discharge scenarios (18,700 lbs per six months for a SLD extension discharge and an approximately 3,500 lbs Se per six months for a targeted SJR discharge). The forecasts are for the low flow season of a dry year, which is the most relevant time period for the migratory predators (see discussion below). The forecasts include consideration of all three possible reactivity scenarios (C1/AE3, C2/AE2, and C3/AE1). Shown for comparison, is a range of threshold Se concentrations for adverse effects on predators based on Se concentrations in liver tissue. The guidelines illustrated show a range from 20 to 50 μg Se/g dw based on data compiled in Tables 13 through 15.

White sturgeon, surf scoter, greater scaup, and lesser scaup are all in the estuary during the fall and early winter, when Se concentrations rise to their highest concentrations in bivalves. White sturgeon generally migrate to freshwater in March to breed; the migratory waterfowl move north for the same purpose shortly thereafter. A lag occurs in the decline of Se concentrations in bivalves in response to increased river inflows, so in most years that have been studied, high Se concentrations in bivalves extend into February or March. A further lag is expected in the response of predators to changing Se concentrations in their food. Thus, the burden of Se these migratory predators would carry as they leave the Bay-Delta would probably be reasonably close to that forecast in Table 32. The low flow condition forecasts may depict the high-end of the risk to these animals, but that is an ecologically reasonable expectation of exposure.

The Se concentrations in tissues of predators that occur when 18,700 lbs Se are released in six months from an SLD extension are well above thresholds for adverse effects (even when full latitude is given for uncertainties about linkages between tissue concentrations and effects). There is no condition when a SLD extension carrying such loads would not greatly threaten these species. The SJR targeted load of approximately 3,500 lbs per six months also threatens these species if partitioning of Se follows the suspended sediment partitioning observed in the past. If partitioning to particulate Se follows the Kd typical of shallow sediment, bivalve bioaccumulation would be similar to what probably existed prior to refinery cleanup, with a resultant forecast of risk similar to that forecast to exist prior to cleanup. This forecast is another line of evidence that the targeted load of 3,500 lbs Se per six months, if conveyed to the Bay-Delta by the SJR, would have the effect of replacing the Se scheduled for removal through treatment by the oil refiners in 1998 (Table 10).

CONCLUSIONS

Cumulative Impacts on the Bay-Delta

Some uncertainty characterizes transformations and other aspect of the analysis given above. However, enough is known about the biogeochemistry and biotransfer of Se that, using multiple lines of evidence, the relevant conditions and outcomes can be bracketed for the Bay-Delta. The model and forecasts demonstrate that many of the most likely combinations of load, hydrology, climate, Se reactivity, and Se bioavailability pose a significant ecological risk to the Bay-Delta. In general, SLD discharges that would meet demands for drainage pose risks to fish and bird reproduction and the risk of fish extinction via contamination of their invertebrate food. If biogeochemical conditions like those today in the Bay-Delta predominate during projected Se discharges, low flow periods would be the time of greatest risk for fish and bird species, especially those that include filter-feeding bivalves among their prey. Where Se undergoes reactions typical of low flow or longer residence time, highly problematic bioaccumulation is forecast to result. There are some conceivable scenarios of increased Se discharge to the Bay-Delta where the potential of risk is reduced. For example, the targeted load scenario for the SJR results in prey in the Bay-Delta containing Se concentrations less than the threshold of effects for predators based on food, but only if reactivity is low during low flow seasons.

Most of those conditions are of low likelihood in that such low particulate and suspended matter reactivity is not typical of the Bay-Delta. Discharge of Se from the SJV would be predominantly selenate, rather than the selenite released by refineries prior to 1998. Transformation of selenate to particulate Se is observed throughout nature where residence times are extended. The efficiency of this transformation and the resulting particulate Se concentrations are key to forecasting Se bioaccumulation and effects.

- *Dry year and wet year, low flow season*

The dry years and low flow seasons will be the ecological bottleneck (the times that will drive impacts) with regard to Se. Surf scoter, greater and lesser scaup, and white sturgeon arrive in the estuary during the low flow season and leave before high flows subside. Animals preparing for reproduction, or for which early life stages develop in September through March, will be highly vulnerable. So, low flow forecasts are probably the most relevant to describe their exposures.

A cumulative summary for the low flow season of a dry year compiles Se concentrations for each media employed in our analysis (water, sediment, invertebrate, predator), along with guidelines or concentrations where biotic effects are expected (Table 33). The forecasts show conditions at the head of the estuary for a range of inputs (6,800; 18,700; or 44,880 lbs released per six months**)**. We assume a particulate transformation of $3 \text{ X } 10^3$ (C2) indicative of shallow sediment Bay-Delta conditions and a generic bivalve AE of 0.56 (AE2) to reflect bioaccumulation potential. In general, the lower range of guidelines for waterborne, particulate, dietary, and predator tissue Se is exceeded in every forecast considered in Table 33 where the input is from a proposed SLD extension. In these dry year/low flow season forecasts, the upper range of guidelines is exceeded in all forecasts except that for the concentration of a generic bivalve (food) at the lowest load considered (6,800 lbs per six months). However, that concentration in prey does result in exceedance of the guideline for white sturgeon and greater and lesser scaup liver.

If a SLD extension is constructed and it discharges during low flow seasons, a high hazard seems likely, with loss of fish and bird species. If an out-of-valley resolution to the drainage problem results in carefully managed discharges of Se to the Bay-Delta via the SJR (for example at 3,500 lbs per six months), the risks are less than for those forecast for a proposed SLD extension. However, for the low flow season of a dry year, Se concentrations in prey and predators are forecast that are similar to Se concentrations observed (and forecast) during conditions in the Bay-Delta prior to refinery cleanup.

These concentrations are in the range of threshold Se concentrations for adverse effects on predators based on both Se concentrations in prey (food) and in predator liver tissue. Thus, selenium from the SJV replaces, in terms of food web exposure and effects, the Se removed in refinery cleanup. Selenium contamination documented from 1986 to 1996 was sufficient to threaten reproduction in key species within the Bay-Delta estuary ecosystems and result in human health advisories.

Concentrations less than the threshold of effects for predators based on food were found in two forecasts for the low flow season of both wet and dry years, but only if:

- the proposed SLD discharge is 150 cfs (half the capacity) and the drainage is treated to attain a concentration of 50 μg Se/L (6,800 lbs per six months) and if Se transformation values or reactivity is low (C3/AE1) in the Bay-Delta; or
- the SJR discharges 3,500 lbs per six months and if Se transformation values or reactivity is the lowest found in any of the receiving waters studied previously (C3/AE1).

The necessary low reactivity is unprecedented in the Bay-Delta during low flows, so this seems an unlikely scenario.

- *Wet year, low and high flow seasons*

High flow conditions afford some protection under certain forecast conditions. Under these conditions, there are some conceivable scenarios where the potential of risk can be reduced. Concentrations less than the threshold of effects for predators based on food are found in wet years, if discharges of 6,800 lbs or 18,700 lbs via a SLD extension or 3,500 lbs via the SJR per six months are released during high flows and reactivities are that of bed sediment or lower (C2 and C3). At the lower SJR input load, a higher reactivity (C1/AE3 or AE4) also results in prey of < 10 μg Se/g, but not at SLD input loads of 6,800 lbs or greater per six-month.

If concentrations in the SJR are regulated under a concentration management plan, increased SJR inflows will result in increased input loads to the Bay-Delta. Under this scenario, the low flow season of a wet year might be more vulnerable than a dry year depending on the regulated concentration for the SJR (Figure 19). Higher concentrations result because the higher Se load during the low flow season of a wet year may not be offset as much by increased flows as those that occur seasonally. Hence, meeting a triple goal of releasing a specific load during a limited period of naturally high flows and keeping concentrations below a certain objective to protect against bioaccumulation may not always be attainable.

As some forecasts show, some releases during high flows may carry less direct risk for fish extinctions. However, it is important that releases during high flows be studied carefully before it is concluded that they lower risks. The fate of Se that enters the Bay-Delta estuary during high inflows is not fully known. For example, it is not known how much is retained and reacts during subsequent low flow periods or how much is transported to the South Bay during high flows and subsequently retained (Conomos et al., 1979; 1985; Nichols et al., 1986; Peterson et al., 1989). Also during high inflows, highly contaminated particulate material from the SJR and/or the SLD is most likely to add to the Se load in the estuary.

- *Implications for water quality criteria for the protection of aquatic life*

In many forecasts, the considered load scenario results in Se concentrations in prey and predators that equal or exceed Se concentrations forecast and measured in the Bay-Delta prior to refinery cleanup. In some forecasts, Se concentrations in the Bay-Delta remained below the 2 μg Se/L water quality criterion proposed for the protection of aquatic life, but those predators using the specific bioaccumulation pathway from sediment and benthic/suspended biomass to bivalves were, nevertheless, impacted. Our forecasts suggest that even at waterborne Se concentrations at the head of the estuary of 1 μg Se/L, all risk of adverse effects cannot be eliminated.

Extent and Sustainability of Agricultural Discharge from the San Joaquin Valley

Taking a broad view, two lines of evidence were used to show the general magnitude of the accumulated Se reservoir in the western SJV. Calculations at the lower range of projections show that long-term reduction in Se discharge would not be expected for 63 to 304 years, if Se were disposed of at a rate of approximately 42,500 lbs per year. Drainage of wastewaters outside of the SJV may slow the degradation of SJV resources, but drainage alone cannot alleviate the salt and Se buildup in the SJV, at least within a century, even if no further inputs of Se from the Coast Ranges occur. The amounts of ground water, salt, and Se that have accumulated in the internal reservoir of the SJV may make management of only the annual imbalance of input greater than output impractical.

However, forecasts of annual SJV agricultural discharges provide a basis for determining the upper and lower limits of Se discharge from the western SJV (Tables 6 to 9; 17). Secondarily, the projections provide the basis for determining the magnitude of Se load reductions that may become necessary to achieve a specific targeted load of Se for environmental or restoration targets or objectives. To narrow the range of possibilities in our analysis, agricultural inputs or discharges were divided into three groups depending upon management scenarios:

- *Supply-driven management.* A range of 3,000 to 8,000 lbs Se per year was assumed to address environmental protection via a targeted load that cannot be exceeded. For example, using different modes of conveyance:
  - Current load limits for the Grassland subarea are from 5,661 to 6,660 lbs Se per year. Grassland subarea loads modeled for the SJR as part of TMDL regulation to meet the 5 µg Se/L concentration objective in the SJR are approximately 1,400 to 6,500 lbs per year. The state enacted Grassland subarea drainage prohibition is 8,000 lbs per year (Tables 5 and 8; and Appendix C).
  - Although no environmental review of the impact of potential Westlands subarea loads has been done since the ecological disaster at Kesterson National Wildlife Refuge occurred, a Westlands subarea load estimate as part of evidentiary hearings is 8,160 lbs Se per year (assuming 200,000 affected acres; drainage generation of 0.3 acre-feet per acre per year; and a Se concentration of 50 µg Se/L) (Table 7). Thus, a load of 8,000 lbs Se per year may be a lower limit of discharge via a proposed SLD extension.
- *Demand-driven load with management of land and/or drainage quality.* A range of 15,000 to 45,000 lbs Se per year was assumed to address agricultural needs, to some degree, for draining saline or waterlogged soils. In this scenario, the quality and quantity of the drainage are controlled by managing volume per acre and/or quality of the drainage. For example: a range of loads projected from the amount of *problem water* or subsurface drainage defined by the SJV Drainage Program for year 2000 with implementation of the management plan (demand driven volume) in conjunction with a concentration of 50 µg/L Se (controlled concentration), yields a Se load range of 19,584 to 42,704 lb Se per year (Table 6).
- *Demand-driven load with minimum management.* A range of 45,000 to 128,000 lbs per year seems possible if the demand for restoring saline soils drives drainage and neither quantity nor quality objectives can be (or are chosen to be) met. For example, a range of loads projected from the amount of *problem water* defined by the SJV Drainage Program for year 2000 without implementation of the management plan (demand driven volume) in conjunction with a concentration of 150 µg/L Se (non-controlled concentration), yields a Se load range of 42,704 to 128,112 lbs Se per year.

Graphical tools such as presented in Appendix B (Figures, B2 to B3) could help model additional probable scenarios of drainage selected for each subarea.

Implications and Monitoring Needs

Implications for water management using our approach and range of loading forecasts are:

- The most significant impacts of irrigation drainage disposal into the Bay-Delta will occur during low flow seasons and especially during low-river flow conditions in dry or critically dry years. Dry or critically dry years have occurred in 31 of the past 92 years; as noted earlier, critical dry years comprised 15 of those years. Any analysis of Se effects must take the influences of variable river inflows into account.
- Selenium impacts in the Bay-Delta also could increase if water diversions increase or if SJR inflows increase with concomitant real-time discharge of Se that increases Se loading (i.e. the Se issue and the water management issues are tightly linked).
- Construction of an extension of the SLD would increase Se exposures of Bay-Delta organisms under any scenario partly because the entire load is unequivocally conveyed directly to the Bay-Delta. The greatest risks occur if discharge is continuous through high and low flow periods. Discharges from a SLD extension are especially problematic if they are constant through low inflow periods, when the dilution capacity of the estuary subsides dramatically because of diversions of freshwater inflows. Freshwater diversions, the resultant volume of inflow, and the degree of treatment of the waste are critical in determining the extent of the impact of a SLD extension.
- Treatment also may be important in determining source loads impacts. Treatment technologies applied to source waters may affect both the concentration and speciation of the effluent. For example, a treatment process could decrease the concentration of Se in the influent, but result in enhanced Se food chain concentrations if speciation in the effluent changes to increase the efficiency of uptake.

We view low flow conditions as the bottleneck that will determine the effects of Se on the ecological health of the Bay-Delta. Biological damage once per year can limit populations of species with a generation time of more than a year; biological damage incurred once per year can be carried over into the remainder of the year. Exposures to Se are probably near their maxima when migratory species leave the estuary, enhancing risk of biological damage. Animals that will be most vulnerable to Se effects probably include those that feed on filter-feeding benthos like bivalves and those that are active (i.e., preparing for reproduction or for which early life stages develop) in the estuary in September through March.

If water quality criteria are to be employed in managing Se inputs, the composite freshwater Se input concentration might be managed as if it were a point source discharge. The calculation is a simple way to take into account hydraulic and inflow conditions that interact to determine the composite endmember Se concentration that is the starting point for determining the exposure that Bay-Delta organisms will experience.

Various guidelines and criteria were employed as reference points in this report. These may not be, individually, realistic indications of ecological risk. For example, in the Bay-Delta neither the USEPA criterion of 5 μg Se/L nor the recommended USFWS criterion level of 2 μg Se/L alone, would be sufficient to protect the estuary if Se transforms to particulate concentrations at a Kd of greater than 10^3. The most effective interpretation includes monitoring data and development of guidelines for all critical media. We see the need for systematic long-term monitoring as crucial to protection of ecosystems receiving Se discharges. In addition to loads and water column concentrations, risk is affected by speciation, transformation to particulate forms, particulate concentrations, bioaccumulation, and trophic transfer to predators. Given below is a sampling plan that includes sampling of media and organisms that are specific to vulnerable food webs. Used in combination, such data and criteria might be the most useful way to manage Se in an ecosystem.

We propose that all processes that link Se load to predator effects be monitored as a feasible approach for site-specific analysis. The linked processes provide the necessary framework. Monitoring, as conceptualized below, would sample critical environmental components at a frequency relevant to each process to determine trends in Se contamination or changes in processes that determine fate and effects of Se.

- In any site-specific analysis of Se impacts, it is important that "site" be defined by all components of its hydrologic unit (e.g., Lemly, 1999b). Hydrologic models would serve as a basis for developing the infrastructure of this hydrologic unit. Specifically, the Bay-Delta ecosystem is connected to the SJR ecosystem, thus warranting consideration of the vulnerability of downstream water bodies when considering evaluation of upstream source waters. Toxicity problems may not appear equally in all components of a hydrologic unit because some components may be more sensitive than others. For example, the SJR, as a flowing water system may be less sensitive to Se effects (especially if selenate dominates inputs) than adjacent wetlands, the Delta or the Bay, where residence times and biogeochemical transformations of selenate are more likely.

- Multiple-media guidelines provide, in combination, a feasible reference point for monitoring. A linked or combined approach would include all considerations that cause systems to respond differently to Se contamination. The critical media defined here are water, particulate material, and prey and predator tissue. Monitoring plan components necessary for a mass balance approach include source loads of Se; concentrations of dissolved Se and suspended Se; Se speciation in water and sediment; assimilation capacities of indicator food chain organisms; and Se concentrations in tissues of prey and predator species. Determination of transformation efficiency and processes that determine Kd's of Se in Bay-Delta and SJR are crucial to relate loads to bioaccumulation, rates of transfer, and effects. Trace elements sequestered in bed sediments and in algal mats would be a part of recommended mass balance considerations.
- Invertebrates may be the optimal indicator to use in monitoring Se because they are practical to sample and are most closely linked to predator exposure. Knowledge of optimal indicators in the Bay-Delta and SJR are necessary to fully explore feeding relationships. Resultant correlations with Se bioaccumulation in food webs are a part of this process.
- Determination of food web inter-relations will help identify the most vulnerable species. Specific protocols that include life cycles of vulnerable predators including migratory and mobile species would then document Se effects for the species most threatened.
- Little is known about Se concentrations in the Delta, yet this is the system that could be most impacted by Se discharges from the SJV. This is the transition zone between the Bay and the largest potential source of Se. It is an area of great biological value itself and an area of great emphasis in CALFED's restoration effort. The fate of Se in the Delta will be a key in determining the extent to which Se contamination will impede restoration of the estuary.
- The fate and effects of Se in the SJR are not well known. Given the possibility of Se concentrations in this ecosystem that may occasionally be greater than the current criterion of 5 μg/L or the proposed criterion of 2 μg/L, it will be essential to investigate and determine the fate and effects of Se in this system. In short, if management and regulatory measures to restore the SJR ecological resources to their former level of abundance are to be effective, then

the biogeochemistry of Se, ecology, and hydrodynamics in this system must be further investigated and understood.

- A mass balance of Se through the estuary is crucial because internal (oil refinery) and external (agricultural drainage) sources of Se are changing as a result of management. In the past (1986 to 1995), cumulative agricultural loading to the SJR was estimated at approximately 100,000 lbs Se (Presser and Piper, 1998). Currently, Se is discharged through Mud Slough to the SJR at the rate of approximately 6,000 to 8,000 lbs per year. The ultimate fate of Se from these past and current agricultural discharges is not known. At a minimum, a mechanism for tracking Se loading via oil refineries and the SJR is needed based on SJR, Sacramento River, and Bay-Delta hydrodynamics. Monitoring needs to measure the on-going status of the system in terms of inputs, storage in sediment, throughput south via the Delta-Mendota Canal and California Aqueduct, and throughput north to the Bay.
- Storms and high flow years will be times of increased regional discharge of drainage containing high concentrations and loads of Se. Violations of water quality criteria and load targets could result on a re-occurring basis, if the precipitation-dependence of the Se inflows is not recognized. The long-term effects of such occurrences on wetlands, wetland channels, the Delta and the Bay need to be better understood. The possibilities of long-term storage after such conditions and the efficiency of bioaccumulation during varying conditions of flow should be studied.
- In view of the analysis of the existing Se reservoir in the SJV, consideration of the degradation of groundwater reservoirs needs to be a factor in management scenarios. Short-term management that results in more storage than leaching will result in more degradation of aquifers. Mass balance considerations should include a "storage" term, not only input and output terms. Monitoring and assessment of storage also will show if treating discharge on an annual basis will suffice to manage the current regional imbalance of water, salt, and Se.

We have demonstrated and thoroughly reviewed the justifications for a methodology that employs existing knowledge of each factor in a sequence of linked processes that control ecological effects of Se. We have incorporated these linked processes into an internally consistent evaluation using multiple lines of evidence. Any future analysis of impacts from Se discharges via the SJR or a proposed SLD extension to the Bay-Delta should be at least as complete and could profitably build from the framework presented here. For the Bay-Delta, this new tool is used in site-specfic forecasts to evaluate Se effects based upon the major processes leading from loads through consumer organisms to predators. We conclude that credible protective criteria need to be applicable to vulnerable food webs and to be based on contaminant concentrations in sources such as particulate material that most influence bioavailability. Bivalves appear to be the most sensitive indicator of Se contamination in the Bay-Delta.

ACKNOWLEDGMENTS

We wish to acknowledge: 1) technical and policy reviews by Marc A. Sylvester, Water Resources Division of the U.S. Geological Survey; 2) technical reviews by Steve Hamilton, Biological Resources Division of the U.S. Geological Survey; and Joy Winckel of the U.S. Fish and Wildlife Service; and 3) grant review by Gail Louis and Philip Woods of the U.S. Environmental Protection Agency. This work was performed with the support of a U.S. Environmental Protection Agency interagency funding agreement (EPA/IAG DW 14955347-01-0) and cooperative funding agreements with Contra Costa County and Contra Costa Water District. We wish to thank Gail Louis, Eugenia McNaughton and Michael Boots of U.S. Environmental Protection Agency, John Kopchik of Contra Costa County, and Richard Denton of Contra Costa Water District for their support during the preparation of our model. Mark Huebner of the Water Resources Division provided technical support with data and figures. And lastly, the long-range vision of T. John Conomos within the U.S. Geological Survey and the goals of the Water Resources Division National Research Program have made this report possible.

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