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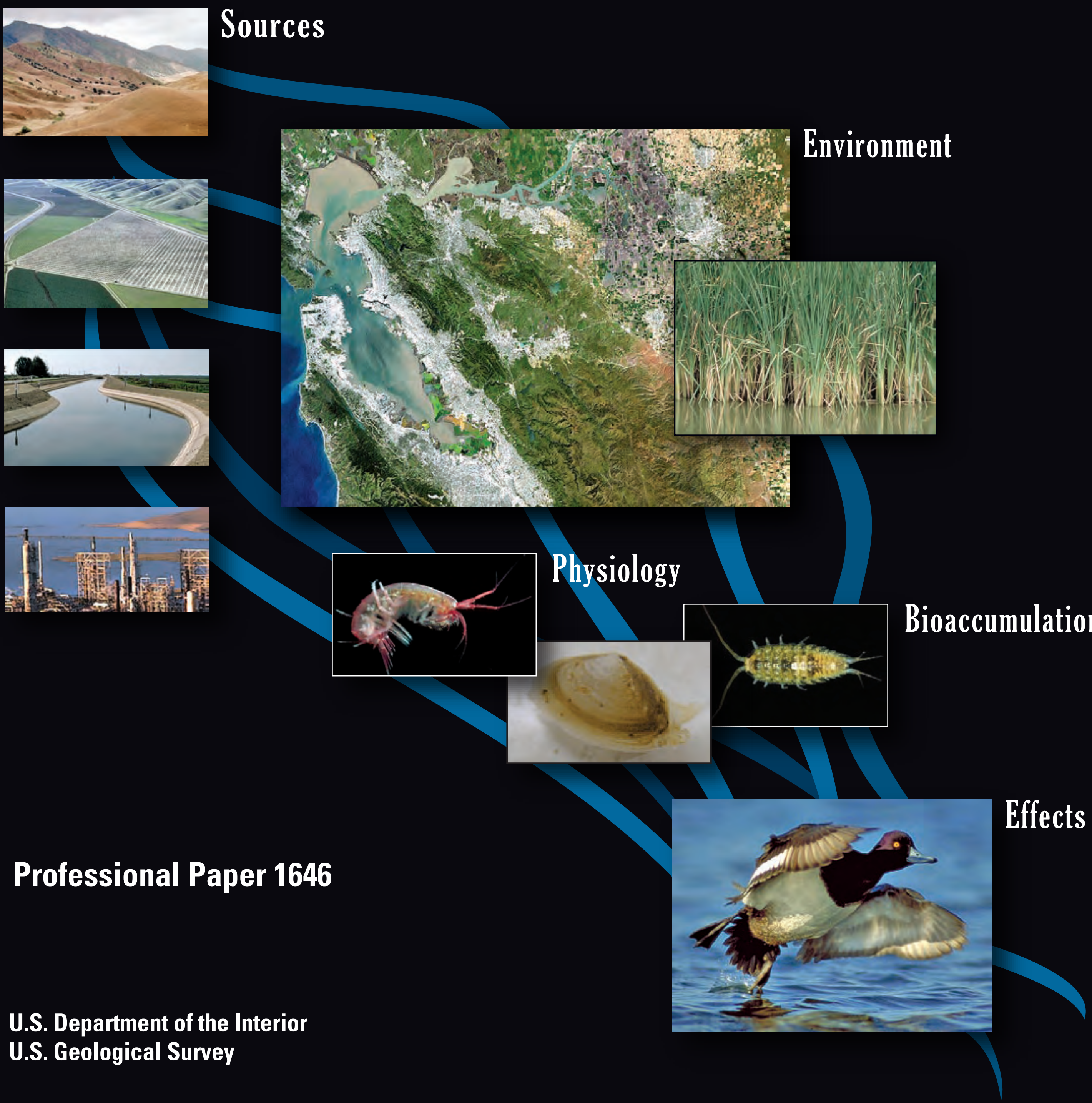
Forecasting Selenium Discharges to the San Francisco Bay-Delta Estuary: Ecological Effects of a Proposed San Luis Drain Extension



Professional Paper 1646

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COVER PHOTOGRAPHS

Sources
California Coast Ranges adjacent to the western San Joaquin Valley
Irrigated farm fields in the western San Joaquin Valley
A section of the San Luis Drain presently being used
Oil refinery adjacent to San Francisco Bay

Environment
Satellite view of San Francisco Bay-Delta Estuary with close-up of wetland environment

Physiology/Bioaccumulation
Mysid
Clam
Amphipod

Effects
Lesser scaup in flight

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

Theresa S. Presser and Samuel N. Luoma

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Conversion table

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
Volume		
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic inch (in^3)	0.01639	liter (L)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	7.4805	gallon (gal)
cubic foot (ft^3)	0.7646	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
Flow rate		
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	1.98346	acre-foot per day (acre-ft/d)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

AE	Assimilation efficiency
Central Valley Board	California Central Valley Regional Water Quality Control Board
CALFED	A collaboration among 25 State and Federal agencies to improve water supplies in California and the health of the San Francisco Bay-Delta Estuary
Department of Fish and Game	California Department of Fish and Game
Drainage Implementation Program	San Joaquin Valley Drainage Implementation Program
Drainage Program	San Joaquin Valley Drainage Program
Department of Water Resources	California Department of Water Resources
DYMBAM model	Dynamic Multi-Pathway Bioaccumulation Model
Interagency Drainage Program	San Joaquin Valley Interagency Drainage Program
State Board	California State Water Resources Board
K_d	Partitioning coefficient
San Francisco Bay Board	California San Francisco Bay Regional Water Quality Control Board
Se	Selenium
TDS	Total Dissolved Solids
USBR	United States Bureau of Reclamation
USDOI	United States Department of the Interior
USEPA	United States Protection Agency
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WY	Water year

Notes

The general term bioaccumulation can be applied to all of the biological levels of selenium transfer through the food web, but in this report the term is used explicitly in reference to particulate/invertebrate bioaccumulation.

A review by Coan (2002) concluded that the San Francisco Bay species *Potamocorbula amurensis* is now the genus *Corbula*, but the species name is still unclear. Because of this uncertainty, reference to the bivalve is now suggested as *Corbula* (*Potamocorbula*) *amurensis* (Thompson, 2005). However, we have retained the name *Potamocorbula amurensis* in this report to support reference to earlier seminal literature.

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

Theresa S. Presser and Samuel N. Luoma

Abstract

Selenium discharges to the San Francisco Bay-Delta Estuary (Bay-Delta) could change significantly if federal and state agencies (1) approve an extension of the San Luis Drain to convey agricultural drainage from the western San Joaquin Valley to the North Bay (Suisun Bay, Carquinez Strait, and San Pablo Bay); (2) allow changes in flow patterns of the lower San Joaquin River and Bay-Delta while using an existing portion of the San Luis Drain to convey agricultural drainage to a tributary of the San Joaquin River; or (3) revise selenium criteria for the protection of aquatic life or issue criteria for the protection of wildlife.

Understanding the biotransfer of selenium is essential to evaluating effects of selenium on Bay-Delta ecosystems. Confusion about selenium threats to fish and wildlife stem from (1) monitoring programs that do not address specific protocols necessary for an element that bioaccumulates; and (2) failure to consider the full complexity of the processes that result in selenium toxicity. Past studies show that predators are more at risk from selenium contamination than their prey, making it difficult to use traditional methods to predict risk from environmental concentrations alone. This report presents an approach to conceptualize and model the fate and effects of selenium under various load scenarios from the San Joaquin Valley. For each potential load, progressive forecasts show resulting (1) water-column concentration; (2) speciation; (3) transformation to particulate form; (4) particulate concentration; (5) bioaccumulation by invertebrates; (6) trophic transfer to predators; and (7) effects on those predators. Enough is known to establish a first-order understanding of relevant conditions, biological response, and ecological risks should selenium be discharged directly into the North Bay through a conveyance such as a proposed extension of the San Luis Drain.

The approach presented here, the Bay-Delta selenium model, determines the mass, fate, and effects of selenium released to the Bay-Delta through use of (1) historical land-use, drainage, alluvial-fill, and runoff databases; (2) existing knowledge concerning biogeochemical reactions and physiological parameters of selenium (e.g., speciation, partitioning between dissolved and particulate forms, and bivalve assimilation efficiency); and (3) site-specific data mainly from 1986 to 1996 for clams and bottom-feeding fish and birds. Selenium load scenarios consider effluents from North Bay oil refineries and discharges of agricultural drainage from the San Joaquin Valley to enable calculation of (a) a composite freshwater endmember selenium concentration at the head of the estuary; and (b) a selenium concentration at a selected seawater location (Carquinez Strait) as a foundation for modeling. Analysis of selenium effects also takes into account the mode of conveyance for agricultural drainage (i.e., the San Luis Drain or San Joaquin River); and flows of the Sacramento River and San Joaquin River on a seasonal or monthly basis.

Load scenarios for San Joaquin Valley mirror predictions made since 1955 of a worsening salt (and by inference, selenium) build-up exacerbated by an arid climate and massive irrigation. The reservoir of selenium in the San Joaquin Valley is sufficient to provide loading at an annual rate of approximately 42,500 pounds of selenium to a Bay-Delta disposal point for 63 to 304 years at the lower range of projections presented here, even if influx of selenium from the California Coast Ranges could be curtailed. Disposal of wastewaters on an annual basis outside of the San Joaquin Valley may slow the degradation of valley resources, but drainage alone cannot alleviate the salt and selenium build-up in the San Joaquin Valley, at least within a century.

Load scenarios also show the different proportions of selenium loading to the Bay-Delta. Oil refinery loads from 1986 to 1992 ranged from 8.5 to 20 pounds of selenium per day; with treatment and cleanup, loads decreased to 3.0 pounds of selenium per day in 1999. In contrast, San Joaquin Valley agricultural drainage loads disposed of in a San Luis Drain extension could range from 45 to 117 pounds of selenium per day across a set of historical and future conditions. Components of this valley-wide load include five source subareas (i.e., Grassland, Westlands, Tulare, Kern, and Northern) defined by water and drainage management. Loads

vary per subarea mainly because of proximity of the subarea to geologic sources of selenium and irrigation history. Loads from the Sacramento River, depending on flow conditions, range from 0.8 to 10 pounds of selenium per day. Loads from the San Joaquin River vary depending on restoration and flow conditions, which are considered.

A consistent picture of ecological risk emerges under modeled selenium discharges from a proposed San Luis Drain extension. The threat to the estuary is greatest during low flow seasons and critically dry years. Where selenium undergoes reactions typical of low flow or longer residence time, highly problematic bioaccumulation in prey (food) is forecast. Surf scoter, greater and lesser scaup, and white sturgeon appear to be most at risk because these Bay-Delta predators feed on deposit and filter-feeding bivalves. Recent findings add Sacramento splittail and Dungeness crab to that list. During the low flow season of critically dry years, forecasted selenium concentrations in water, particulate matter, prey (diet), and predator tissue exceed guidelines with a high certainty of producing adverse effects under the most likely load scenario from a proposed San Luis Drain extension. High flows afford some protection under certain conditions in modeled San Joaquin River scenarios. However, meeting a combined goal of releasing a specific load during maximum flows and keeping selenium concentrations in the river below a certain objective to protect against bioaccumulation may not always be attainable. Management of the San Joaquin River on a constant concentration basis also could 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 river inflows.

Prior to refinery cleanup, selenium contamination was sufficient to threaten reproduction in key species within the Bay-Delta ecosystems and human health advisories were posted based on selenium concentrations in tissues of diving ducks. During this time, selenium concentrations in the Bay-Delta were well below the most stringent recommended water quality criterion [1 microgram per liter (1 μg/L)]. Enhanced biogeochemical transformations to bioavailable particulate selenium and efficient bioaccumulation by bivalves characterized the system. If these biogeochemical conditions continue to prevail and agricultural selenium sources replace or exceed refinery sources, ecological forecasts suggest the risk of adverse effects will be difficult to eliminate under an out-of-valley resolution to the selenium problem.

The Bay-Delta selenium model presented here is a systematic approach for conducting forecasts of the ecological effects from selenium on aquatic food webs. It is a new tool that links and models the major processes leading from loads through consumer organisms to predators. It also is a feasible approach for site-specific analysis and could provide a framework for developing new protective selenium foodweb guidelines and predator criteria. Model components that help ensure understanding ecosystems and the basis of environmental protection are (1) contaminant concentrations and speciation in sources, such as particulate material, that most influence bioavailability; (2) bioaccumulation models that calculate concentrations in diet, specifically in bivalves of the Bay-Delta that act as sensitive indicators of selenium contamination; (3) food-web type that determines what animals are threatened and when; and (4) multiple media concentrations (water, particulate material, and tissue of prey and predators) that, in-combination, determine risk or hazard.

Introduction

The sources and biogeochemistry of selenium 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 and others, 1999; Hamilton, 1999; Eisler, 2000; Hamilton, 2004] (fig. 1). Selenium is especially enriched in organic-rich shales that are source rocks for oil, coal, and phosphate ores (Cumbie and Van Horn, 1978; Presser, 1999; Piper and others, 2000; Presser and others, 2004). Release of selenium to aquatic systems is a result of weathering and anthropogenic activities such as refining, power production, and mining. Selenium also is enriched in the soils and runoff derived from these source sedimentary shales in many semi-arid regions developed for irrigated agriculture, such as in the San Joaquin Valley, California (Presser, 1994a, b; Seiler and others, 1999). Salinization of some of these soils is accompanied by selenium contamination that increases the complexity of problems associated with farming of such lands [San Joaquin Valley Drainage Program (Drainage Program), 1990a; Dinar and Zilberman, 1991]. Irrigation, leaching, and generation of subsurface drainage can ultimately contaminate ground and surface waters as storage and export become necessary to sustain agriculture (Presser and Ohlendorf, 1987).

Treatment technologies for selenium have utilized both chemical and biological processes to remove selenium from the water column, but with little operational success or cost-effectiveness [Drainage Program, 1990a; Hanna and others, 1990; San Joaquin Valley Drainage Implementation Program (Drainage Implementation Program), 1998, 1999a]. Use of large-scale biological treatment technologies (such as wetlands or evaporation ponds) has generated serious ecological problems and hazardous selenium wastes for disposal (Presser and Piper, 1998; Skorupa, 1998a; Drainage Program, 1990b). Selenium removal is further hampered by the failure of traditional chemical methods to reduce selenium to levels acceptable for remediation and, in arid regions, by the problem of disposal of associated salts (Drainage Program, 1990a). Remediation has not been established other than that dependent on dilution in a larger body of water [Drainage Implementation Program, 1998; United States Department of the Interior (USDOI) National Irrigation Water Quality Program, 2000]. Management plans for the western San Joaquin Valley that include storage and reduc-

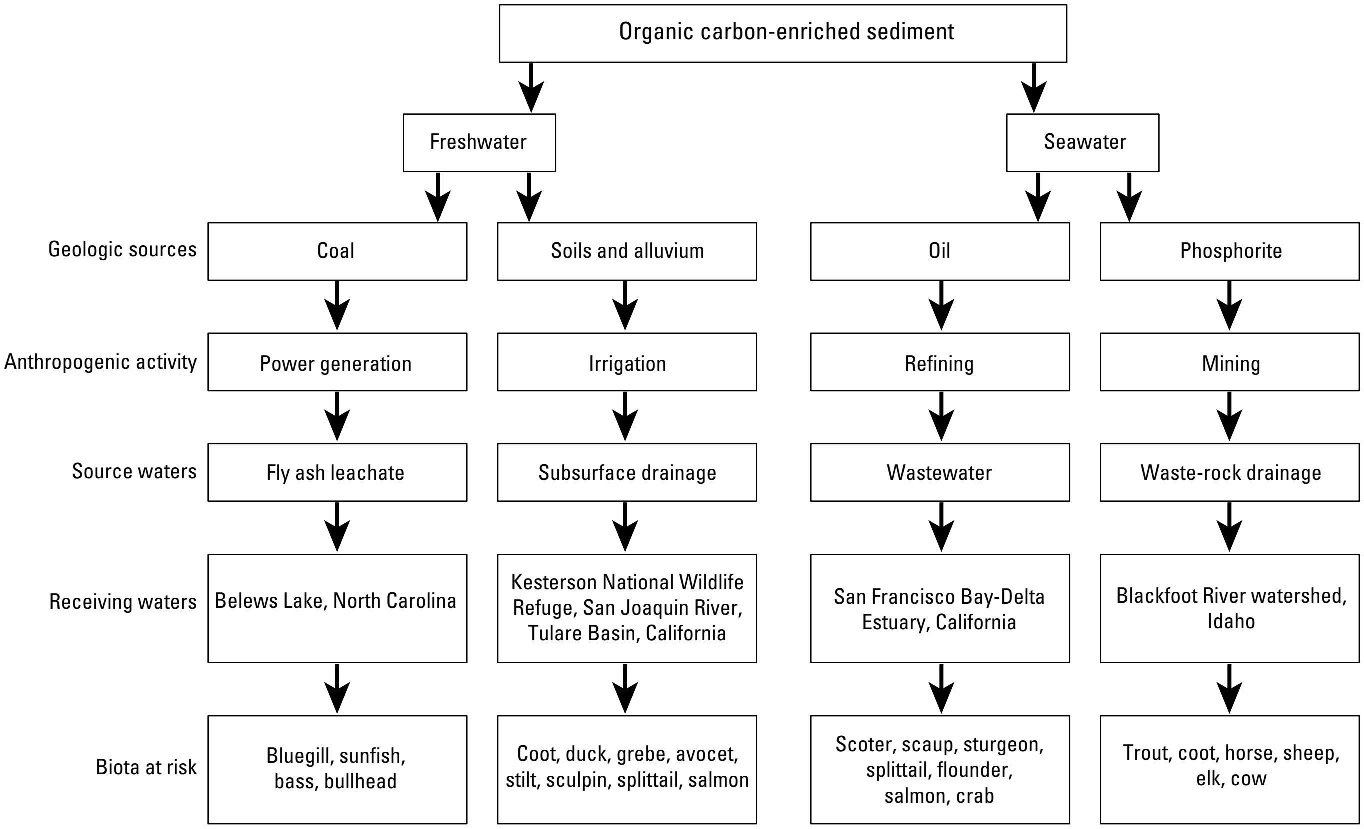

Figure 1. Conceptual model of selenium pollution with examples of source deposits, anthropogenic activities, source waters, receiving waters, and biota at risk.

tion of drainage through source control have been developed, but systematic and comprehensive implementation has not taken place (Drainage Program, 1990a; Drainage Implementation Program, 1991, 1998; Environmental Defense Fund, 1994).

The biogeochemical cycling of selenium and its role as an essential nutrient lead, in general, to the dominance of biological reactions over thermodynamic reactions in aquatic systems and concern based on food webs (Shrift, 1964; Stadtman, 1974; National Research Council, 1976; Measures and Burton, 1978; Cutter and Bruland, 1984; Lemly, 1985; Presser and Ohlendorf, 1987; Oremland and others, 1989; Luoma and others, 1992; Maier and Knight, 1994; Presser, 1994a; Lemly, 1997b; Wang and others, 1996; Luoma and Fisher, 1997; Dowdle and Oremland, 1999; Reinfelder and others, 1998). More specifically, the fate and ecological effects of selenium discharges are determined by a sequence of processes that link loads, concentrations, speciation, bioavailability, trophic transfer, and effects on predators (Luoma and others, 1992; Luoma, 1996; Wang and others, 1996; Reinfelder and others, 1997, 1998; Luoma and Fisher, 1997; Luoma and Rainbow, 2005) (as exemplified for the Bay-Delta, fig. 2). Pathway-specific models allow consideration of (1) speciation and transformation between dissolved and particulate forms (2) biotransfer from different types of suspended/particulate matter (for example, phytoplankton, detritus, and sediment); (3) bioaccumulation via the lower trophic food web; and (4) uptake of food by predator species. Because selenium concentrations can biomagnify during food web transfer (see, for example, USEPA, 1980; Saiki, 1986; Maier and Knight, 1994; Reinfelder and others, 1998; Stewart and others, 2004; Luoma and Rainbow, 2005), upper trophic level species are the species most vulnerable to adverse effects from selenium contamination. Aquatic species found at risk from selenium contamination include ducks, shorebirds, grebes, suckers, salmon, trout, sunfish, sturgeon, and crab (White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991; Luoma and others, 1992; Lemly, 1993a, 1998a, b; Skorupa, 1998a; Hamilton, 1998; Presser and Piper, 1998; Stewart and others, 2004) (figs. 1 and 2). Some species of amphibians and reptiles also may be at risk from selenium [Skorupa, 1998b; U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS), 1998 and amended, 2000].

Analysis of any one of the above sets of processes, in isolation, is inadequate to characterize selenium 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 interpreta-

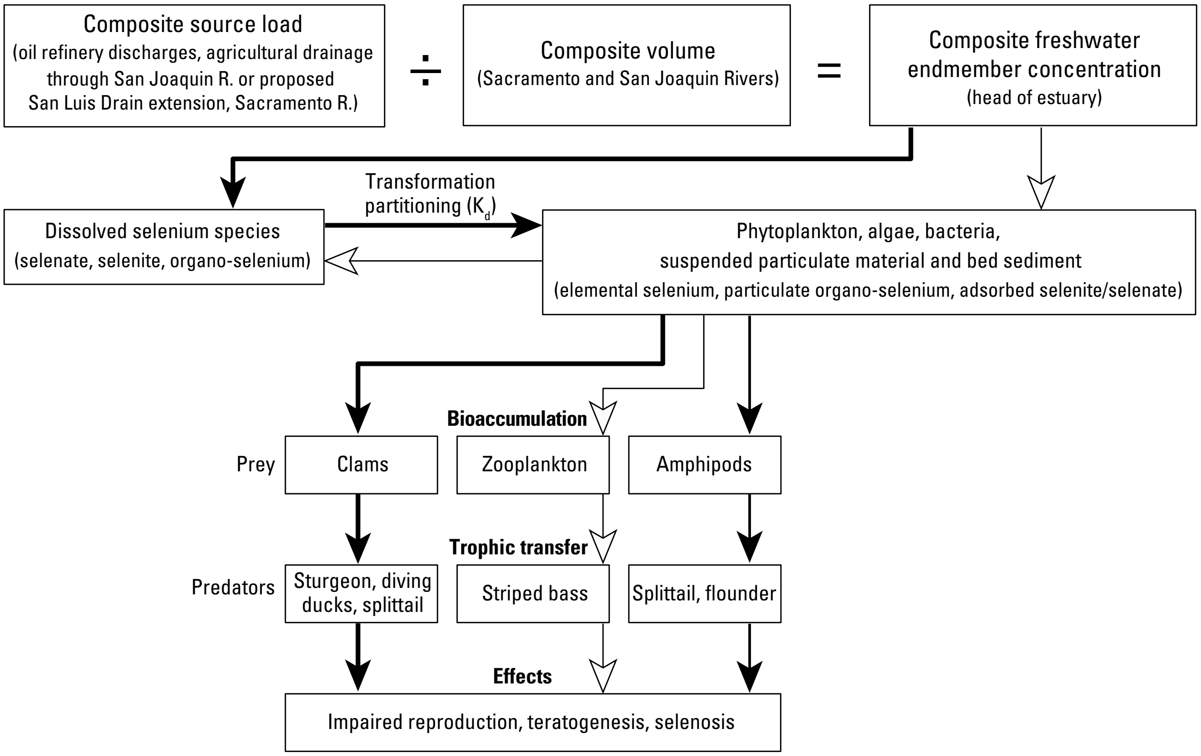

Figure 2. Conceptual model (the Bay-Delta Selenium Model) describing linked factors that determine the effects of selenium on ecosystems. (Note: The general term bioaccumulation can be applied to all of the biological levels of selenium transfer through the food web, but in this report the term is used explicitly in reference to particulate/invertebrate bioaccumulation.)

tions of selenium effects on the environment (see, for example, O'Toole and Raisbeck, 1998; Hamilton and Lemly, 1999; Chapman, 1999; Lemly, 1999a; Skorupa, 1998a, 1999). In view of advances in the understanding of the environmental chemistry of selenium, the USEPA has recently proposed revising selenium criteria for the protection of aquatic life (USEPA, 1998; Renner, 1998; USEPA, 2005).

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 and others, 1999). Selenium issues are of particular concern in the San Joaquin River basin and the Bay-Delta (fig. 3). Here, selenium issues are intricately interwoven with issues of water management, urbanization, irrigated agriculture, and protection of fish and wildlife resources [Conomos, 1979; Conomos and others, 1985; Cloern and Nichols, 1985; Nichols and others, 1986; California State Water Resources Control Board (State Board), 1994, 1999a; USFWS, 1995; Hollibaugh, 1996; Presser and Piper, 1998; CALFED, 1998a, b, 1999a, b, c, d; Thompson and others, 2000; United States Bureau of Reclamation (USBR), 2005b]. The San Joaquin Valley also has suffered major losses of crucial habitat for migratory birds (Gilmer and others, 1982; Vencil, 1986).

The purpose of this report is to present a systematic and comprehensive approach for forecasting the ecological effects of selenium in the estuarine food web under an array of scenarios that could result from different resolutions of water and waste management issues for the San Joaquin Valley and Bay-Delta. The analysis focuses on selenium loads that would result from engineering solutions that convey selenium-laden drainage from the western San Joaquin Valley to the Bay-Delta through a proposed extension of the San Luis Drain (Barcellos, 1986; Wanger, 1994; State Board, 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 and others, 2000; USBR, 2005a). Also considered is using the San Joaquin River as a conveyance facility (the river, in effect, as a drain) because it is the only natural outlet from the San Joaquin Valley. A history is presented of the discussions surrounding construction of the drain and use of the San Joaquin River to convey selenium outside the San Joaquin Valley.

The scope of the analysis involves using empirical observations from the Bay-Delta hydrologic system and mechanistic models to (1) convert proposed selenium loads to concentrations in receiving waters under several scenarios; and (2) forecast bioaccumulation in lower trophic level prey organisms (bivalves) from a likely range of particulate speciation/transformation regimes and bivalve assimilation efficiencies. Selenium concentrations in Bay-Delta clams are compared to

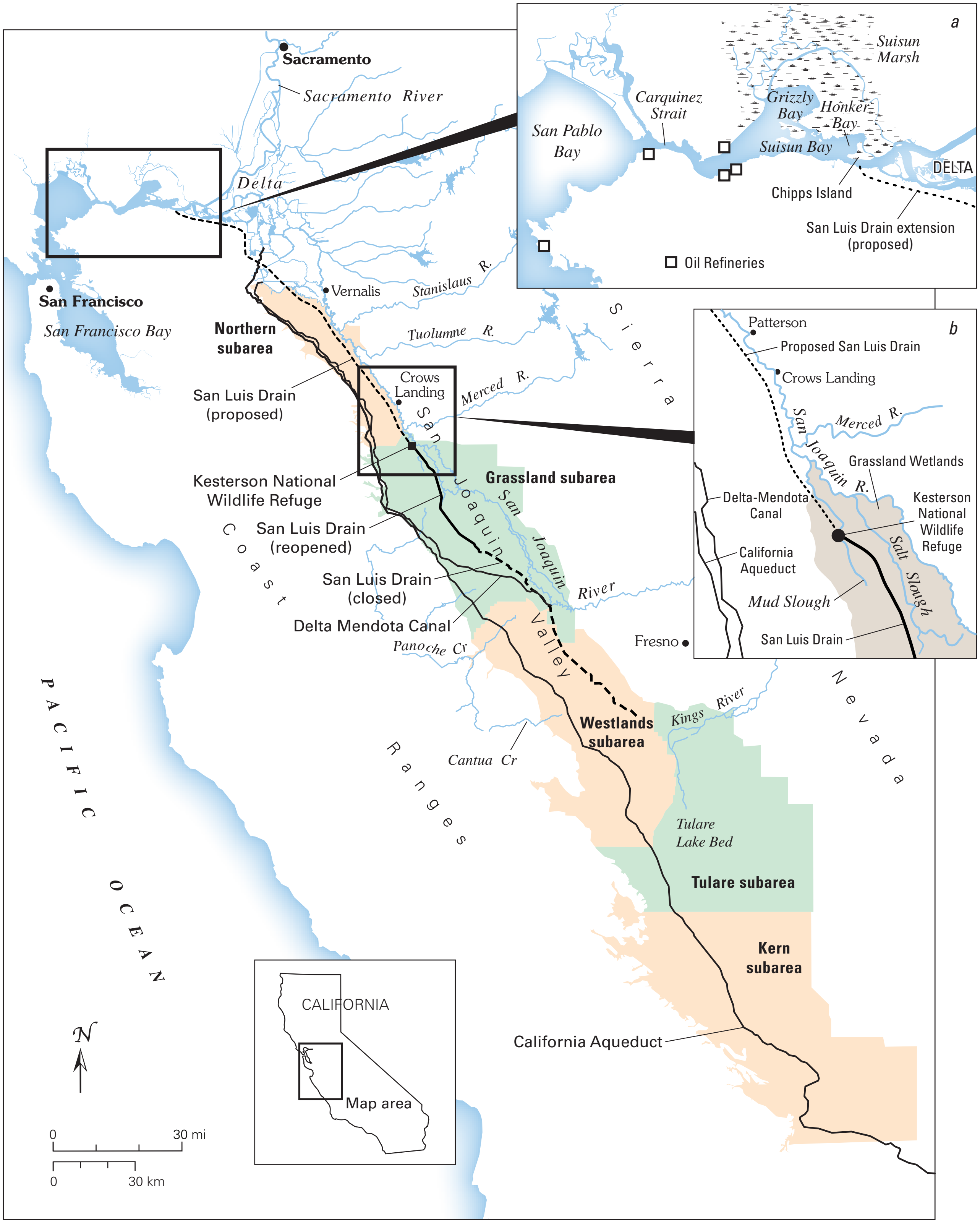

Figure 3. Map showing the San Francisco Bay-Delta Estuary and the San Joaquin Valley of California, with subareas for management of agricultural drainage highlighted (adapted from Presser and Piper, 1998). Insets show details of (*a*) the North Bay including locations of oil refineries; (*b*) San Joaquin River riparian wetlands area including locations of the San Luis Drain, Kesterson National Wildlife Refuge, and Grassland wetland area.

protective dietary selenium guidelines for fish and birds. Selenium concentrations in the tissues of a few key predators are predicted from correlations with concentrations of selenium in bivalves (food) using data from the existing literature. Because the relation between tissue concentrations and adverse effects are relatively constrained for selenium in wildlife, predictions of tissue residues in waterfowl and fish provide a first order estimate of potential adverse effects of selenium discharges.

Presentation and understanding of the processes by which the ecological effects of selenium are evaluated are as important as the specifics of the data and discussion as applied to the Bay-Delta. The general process of a linked bioaccumulation model, which uses a bioindicator organism to assess potential adverse effects on predators, can be applied to other ecosystems subjected to selenium loading. Thus, this approach can help in the development of national or site-specific selenium criteria for aquatic-life and wildlife protection.

Generic Selenium Issues

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

1. Geologic sources of selenium are widespread (fig. 1).
2. Development 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 selenium and ultimately result in the contamination problems found today (see examples in fig. 1).
3. Linked biological and geochemical reactions determine the form of selenium. Geochemical form (speciation) determines how readily selenium enters aquatic food webs, initiates food web transfer, and cycles through particulate matter, consumer organisms, and predators.
4. The biochemistry of selenium is also complicated by selenium being an essential dietary nutrient and a toxicant. Effects can occur in animals at a concentration of selenium in diet only slightly above that which is nutritionally required because the difference is small between the amount of selenium that is adequate and the amount that is toxic (Luckey and Venugopal, 1977; Wilber, 1983; National Research Council, 1976; USEPA, 1980, 1998; Haygarth, 1994; Skorupa, 1998a, b).
5. Hydrologic connections also determine the reactions of selenium. Compartmentalized ecological systems can interact at critical hydrologic junctures such as in estuaries. Seemingly harmless concentrations of selenium in a riverine system may become problematic in downstream impoundments, marshes, or wetlands, where cycling and bioaccumulation are accentuated (Luoma and others, 1992; Skorupa, 1998a; Lemly, 1999b). The geographic scale of selenium issues can extend beyond local conditions and therefore, an analysis of downstream effects needs to follow.
6. Traditional toxicity tests are problematic because they determine toxicity only from direct water-borne exposures. Direct transfer of selenium from solution to animals such as fish and bivalves is a small proportion of exposures.
7. Bioaccumulation and uptake in food is the most important route of selenium transfer to upper trophic level species (Ohlendorf and others, 1986; Saiki and Lowe, 1987; Presser and Ohlendorf, 1987; Lemly, 1985; Luoma and others, 1992; Presser and others, 1994). Selenium efficiently bioaccumulates through aquatic food webs and biomagnifies in many components of the food web (Saiki, 1986; Presser and Ohlendorf, 1987; Luoma and others, 1992; Maier and Knight, 1994; Reinfelder and others, 1998; Stewart and others, 2004; Schlekat and others, 2004). Biomagnification is important when considering effects to upper trophic levels and relating effects to environmental concentrations. If an element is biomagnified at each trophic step, then biota several steps from the base of the food web could be affected to a greater degree than the rest of the food web (that is, predators are more at risk than their prey) (Reinfelder and others, 1998).
8. Invertebrates may be the best indicator for monitoring predator exposure. Consumer species, such as bivalves, integrate the influences of environmental concentrations, speciation, and transformations of selenium and are practical to sample.
9. Bioaccumulation models link food sources to predator animals to predict biotic effects (as exemplified for the Bay-Delta, fig. 2). Bioaccumulation models use species-specific data for assimilation efficiency, ingestion rate of food, rate of loss, and growth rate for prey species.
10. A predator's choice of food, which varies widely among species, results in some trophic pathways being more efficient accumulators of selenium than others (Lemly, 1982, 1985; Luoma and others, 1992; Luoma and Fisher, 1997; Skorupa, 1998a; CH2M HILL, 1996, 1999a; Stewart and others, 2004; Schlekat and others, 2002a, b, 2004). Hence, determination of food webs helps identify which predators are vulnerable to seemingly modest environmental levels or whether more massive contamination is necessary to trigger toxic exposure.
11. Birds and fish (predators) are the two taxa of animals most sensitive (that is, they are the first to express the effects of selenium within the ecosystem) to aquatic selenium contamination, with embryonic and larval life-stages being of particular concern (Ohlendorf, 1989; Ohlendorf and others, 1989a; Hamilton and others, 1990; Lemly, 1996b, c; Skorupa, 1998a, b, c; Hamilton, 2003, 2004). In contrast to many other contaminants, significant environmental damage due to selenium contamination has been well documented. Skorupa (1998a) described case studies showing different degrees of selenium effects in a variety of wetlands and reservoirs affected by agricultural drain-

age, burning of fossil fuels, or refining of oil. An especially well-documented case study exists for Belews Lake in North Carolina where selenium contamination caused reproductive impairment and teratogenesis in fish leading to local extinctions of most fish populations (Cumbie and Van Horn, 1978; Lemly, 1985, 1997a). The most well known case of selenium poisoning in a field environment is at Kesterson National Wildlife Refuge in the San Joaquin Valley of California (Ohlendorf and others, 1986; Presser and Ohlendorf, 1987; Skorupa and Ohlendorf, 1991; Drainage Program, 1990b, c). There, deformity and death in embryos and hatchlings of aquatic bird populations were widespread; toxicity and immune deficiency contributed to the death of adult aquatic birds; multi-species warm-water fish assemblages disappeared; and a high incidence of stillborne fry occurred in pollution-tolerant mosquitofish (Ohlendorf, 1989; Skorupa, 1998a).

12. Although extreme selenium contamination causes death in adult organisms, the responses of greatest concern are impairment of reproductive success (for example, failure of eggs to hatch) and teratogenesis (deformities in embryos and juveniles) in birds and fish (Skorupa and Ohlendorf, 1991). 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, 2004). These organisms efficiently transfer selenium to their eggs. Data exist that relate teratogenesis, hatchability, and reproductive success to selenium concentrations in food, avian eggs, and fish larvae (reviews in Heinz, 1996; Lemly, 1998b; Maier and Knight, 1994; Skorupa, 1998a, b). Dose-response curves for aquatic birds, although varying in sensitivity, are remarkably steep (Skorupa, 1998). Inhibition of growth, mass wasting, depression of the immune system, and oxidative stress also are toxicity endpoints of concern, with winter stress syndrome known to increase the toxicity of dietary selenium to birds and fish during low winter temperatures (Ohlendorf, 1989; Lemly, 1993b, 1998a; CH2M HILL, 1997, 1999b; USFWS and NMFS, 1998 and amended, 2000; Santolo and others, 1999; Holm and others, 2003; Palace and others, 2004). Ecological risk guidelines and a risk index based on selenium concentrations in water, sediment, diet, and tissue (both whole-body and egg) are currently available, with some risk levels still under debate (Peterson and Nebeker, 1992; Engberg and others, 1998; Lemly, 1995; Skorupa, 1998a, b, c; Presser and others, 2004a.)

13. Uncertainty exists in the USEPA selenium criteria for the protection of aquatic life, especially for acute criteria derived from water-only, short-term exposure of surrogate species. The toxicity-testing database does not consider bioaccumulation, although bioaccumulation from food determines the ecological effects of selenium. Uncertainty also exists for chronic criteria based on limited field data for food chain exposure, if few studies are available at the time of criteria promulgation (USEPA, 1992, 1998). A selenium criterion derived primarily from food web exposure would be more relevant to field conditions in aquatic systems.

14. Effects of selenium on human health are of concern [USEPA, 1998 and 2000; California Department of Fish and Game (Department of Fish and Game), 1985, 1986, 1988, all ongoing, 1987; Fan and others, 1988; Drainage Program, 1989, 1990b]. National and state human health advisories restrict consumption of fish when selenium concentrations exceed a certain criterion specific to meal amounts, rate of consumption, and reference dose. Pregnant women, children, and subsistence populations are special categories where contaminated ecosystems and landscapes are a concern. Consumption of wildlife (hunted birds) also can be under advisories.

15. No satisfactory chemical, physical or biological treatment technology yet exists to remove selenium contamination from irrigation drainage waters (Hanna and others, 1990; Hansen and others, 1998; Drainage Implementation Program, 1999a, b, c, d). Treatment technologies that work on small effluent streams are expensive to employ on large volumes of contaminated water (Drainage Program, 1990a; Drainage Implementation Program, 1998; USDOI National Irrigation Drainage Program, 2000). Variations of flow-through wetlands and biological precipitation technologies remain in pilot studies (Hansen and others, 1998; Drainage Implementation Program, 1999a; USBR, 2005), 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 San Joaquin Valley 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 (Drainage Program, 1990a).

Selenium Issues in the Bay-Delta

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

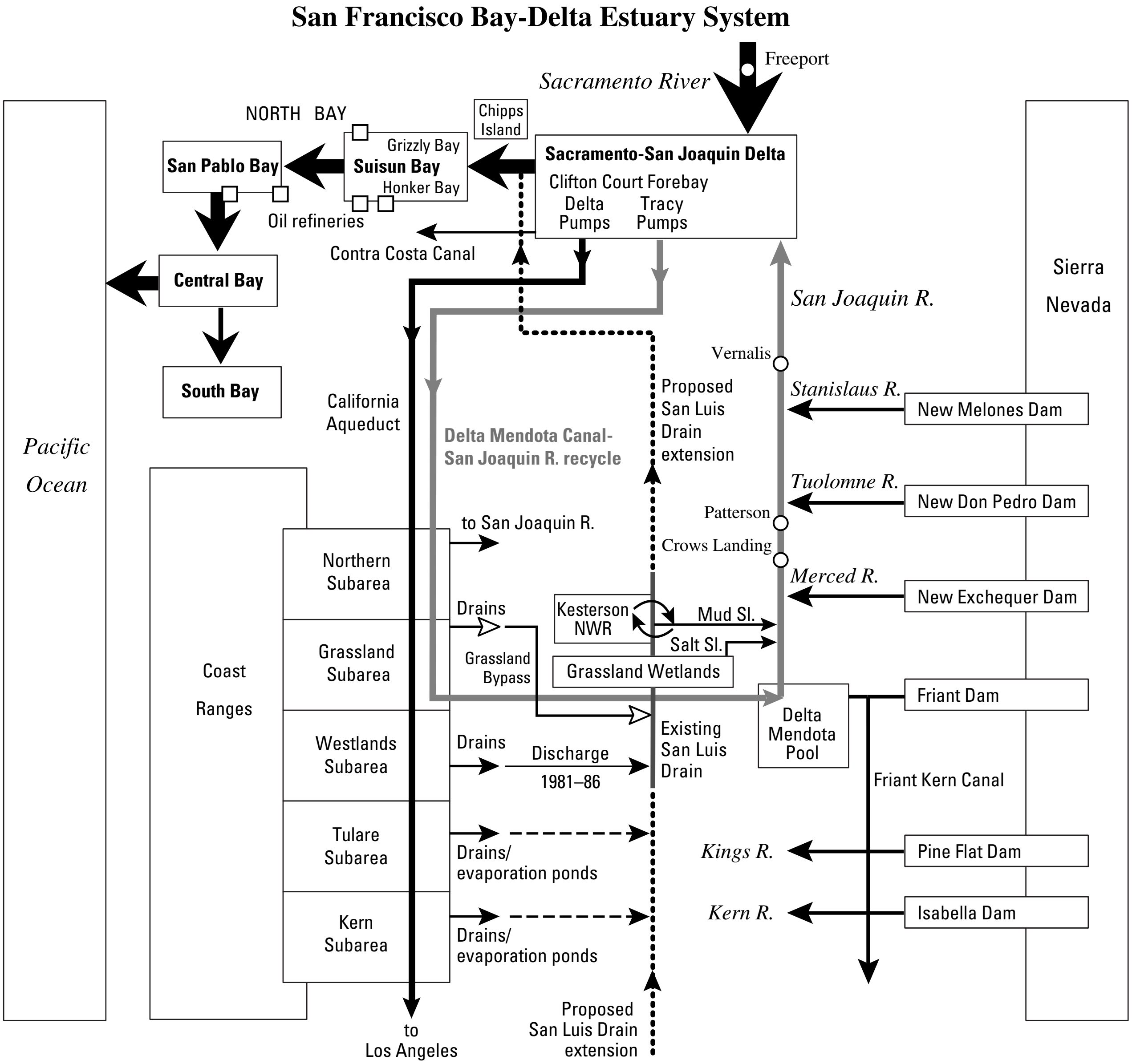

Figure 4. Schematic showing detailed hydrologic connections of the San Francisco Bay-Delta Estuary with the San Joaquin Valley, California (not to scale; enlarged arrows are for emphasis only and are not representational of flow). (Note that the only natural outlet from the valley is the San Joaquin River and that an extension of the San Luis Drain would provide a constructed outlet to the Bay-Delta for agricultural drainage from the western San Joaquin Valley.)

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

1. Selenium contamination exists under present conditions in the Bay-Delta from known sources of selenium within the estuary and in watersheds draining to the estuary. Watershed sources are linked to San Joaquin Valley farmland activities. Here, irrigation of salinized soils has led to management proposals to sustain agriculture by exporting salts and selenium, collected as subsurface drainage, to the Bay-Delta through the San Joaquin River or San Luis Drain [see, for example, State Board, 1985; Drainage Program, 1990a; Presser and Ohlendorf, 1987; Presser and Piper, 1998; Skorupa, 1998a; California Central Valley Regional Water Quality Control Board (Central Valley Board), 1998a, b; USFWS and NMFS, 1998 and amended 2000)(fig.4). Detailed proposals for construction of a collector drain, and more recently for construction of an extension of the existing San Luis Drain, to remove salts and selenium from the San Joaquin Valley have been under consideration for approximately 50 years (table 1; also see detailed discussion in appendix A). Water quality in the San Joaquin River has degraded significantly since the 1940s because of disposal of agricultural wastewater from the San Joaquin Valley (Central Valley Board, 1995). Even though the San Joaquin River flows into the Bay-Delta, selenium sources and contamination linked mainly

to oil refineries within the Bay-Delta are better documented (Johns and others, 1988; Cutter, 1989; Cutter and San Diego-McGlone, 1990). Oil refiners discharge waste from processing selenium-enriched crude oil from the San Joaquin Valley and adjacent Coast Ranges into the North Bay (fig. 3).

2. Selenium contamination documented from 1982 to the mid-1990s was sufficient to threaten reproduction in key species within the Bay-Delta estuary ecosystems [White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991; San Francisco Estuary Project, 1991, 1992; Harvey and others, 1992; California San Francisco Bay Regional Water Quality Control Board (San Francisco Bay Board), 1992a, b, 1993; Luoma and others, 1992; Brown and Luoma, 1995a; Luoma and Linville, 1997; USFWS and NMFS, 1998 and amended, 2000); Linville and others, 2002] (table 2). The most severely threatened species appear to include, but are not restricted to, white sturgeon (*Acipenser transmontaus*), starry flounder (*Platichthys stellatus*), Dungeness crab (*Cancer magister*), surf scoter (*Melanitta perspicillata*), greater scaup (*Aythya marilla*), and lesser scaup (*Aythya affinis*) (Ohlendorf and others, 1986; White and others, 1987; 1988; 1989; Ohlendorf and others, 1989b, c; Urquhart and Regalado, 1991; Luoma and others, 1992; USFWS, 1995; Hothem and others, 1998). From 1989 to 1990 in the North Bay, average selenium concentrations in surf scoter liver tissue and sturgeon flesh exceeded reproductive toxicity guidelines (Heinz, 1996; Lemly, 1998b and 2002) by at least eightfold and twofold, respectively. Currently, populations and catches per unit effort (where applicable) of all 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 selenium concentrations in tissues of prey and predators exceed adverse effect guidelines, selenium cannot be excluded as one.

3. Some food webs in the Bay-Delta may be particularly vulnerable to moderate selenium contamination. Analyses from 1982 through 1996 showed that the animals with the highest selenium tissue concentrations from the North 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-1990s (Linville and others, 2002) than in 1977 through 1990 (White and others, 1987, 1988, 1989; Cutter, 1989; Johns and others, 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 may be the most important route of selenium transfer to upper trophic levels (bottom feeding fish, diving ducks, and crab) in the estuary. Selenium concentrations in *P. amurensis* reached 20 micrograms per gram (µg/g) dry weight in the North Bay in October 1996, exceeding by twofold a dietary guideline (>10 µg/g dry weight) that has been shown with a high degree of certainty to result in adverse reproductive effects to predators.

4. Portions of the Bay-Delta and the San Joaquin River are currently listed by the State as being subjected to contamination from a suite of chemicals (such as mercury, diazinon, PCBs, dioxin, PAHs, and selenium) (Central Valley Board, 1994a, 1998b; State Board, 1999b, c). State or Federal criteria have been exceeded in these listed water bodies, causing adverse aquatic life and human health effects (see, for example, Fairey and others, 1997; Davis and others, 1997; Dubrovsky and others, 1998). Water-quality limited segments of the Bay-Delta listed because of selenium under the Clean Water act as of 2002 are: Sacramento-San Joaquin Delta, Suisun Bay, Carquinez Strait, San Pablo Bay, Central Bay, South Bay, Oakland Inner Harbor, and San Leandro Bay (State Board, 2002). Portions of the San Joaquin River and its tributaries designated as water-quality limited due to selenium are the San Joaquin River from Mud Slough to the Merced River, Mud Slough, the Mendota Pool, and Panoche Creek.

5. Selenium contamination affects the quality of the already limited acreage of wetlands and other crucial habitat in the Bay-Delta (CALFED, 1998a, b, 1999a, b, c, d). The decreasing extent and degraded quality of these wetlands leaves in doubt the future status of many wildlife populations (Harvey and others, 1992; CALFED, 1998a, b; San Francisco Estuary Project, 1999). A recovery plan was deemed necessary for Sacramento/San Joaquin Delta native fishes (USFWS, 1995). The plan includes designation of critical habitat (which means that 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 Sacramento splittail (*Pogonichthys macrolepidotas*) (64 Federal Register 5963) is not currently designated because of recent de-listing from threatened status (68 Federal Register 183, 2003).

6. Environmental safeguards enacted after the ecological crisis at Kesterson National Wildlife Refuge may be inadequate for the specific problems of the Bay-Delta. For example:

    a. The equality of the criterion for the protection of aquatic life and the ecological threshold at which substantive risk occurs (i.e., 5 µg/L selenium) demonstrates a need to establish a set of criteria that fully encompasses both aquatic and semi-aquatic food web components and protects wildlife in addition to aquatic life (Skorupa 1998b; Engberg and others, 1998; USEPA, 1989, 1998, 2005; USFWS and MNFS, 1998 and amended 2000; Reiley and others, 2003). Review and revision of estuary and ocean selenium criteria has not taken place as scheduled,

Table 1. Chronology of authorizing, planning, regulatory, and evidentiary events for construction of a valley-wide drain or a San Luis Drain.

Date	Agency or industry	Event
1950	USBR	Begins Central Valley Project Delta-Mendota Service Area water deliveries
1955	USBR	Feasibility report for drainage canal (300 cubic feet per second capacity; 197 miles length) from the San Joaquin Valley
1960	Federal Law (Public Law 86-488)[a]	Authorizes San Luis Unit of Central Valley Project and makes provision for constructing interceptor drain to the Bay-Delta
1962	USBR	Definite Plan Report for San Luis Unit (includes capacity for other areas)
1965	State of California[a]	Proposes expansion of drainage plans to install valley-wide master drain
1965 to present	U.S. Congress[b]	Includes a rider to Central Valley Project appropriations act specifying development of a plan which conforms with state water quality standards as approved by USEPA to minimize any detrimental effects of the San Luis Unit drainage waters
1967	State of California	Declines to participate in valleywide master drain
1968	USBR	Begin (1) Central Valley Project water deliveries to the San Luis Service Area and (2) construction of San Luis Drain for use by Westlands Water District
1969	Drainage Advisory Group	Issues final report recommending drain to the Delta
1970	USBR and USFWS	Designate Kesterson Reservoir, a regulating reservoir for the San Luis Drain, as a new USFWS National Wildlife Refuge
1972	USBR	Environmental Impact Statement on San Luis Unit filed with Council on Environmental Quality
1975	USBR	Completes 85-mile San Luis Drain to Kesterson Reservoir, 120 miles of collector drains, and 1,200-acre reservoir; agrees to supplemental Environmental Impact Statement on impacts of San Luis Drain
1975	USBR[a]	Halts construction of remainder of San Luis Drain due to Federal budget restrictions and increasing environmental concerns regarding discharge to the Delta
1975	USBR and state water agencies[a]	Recommend completion of the San Luis Drain to the Bay-Delta
1977	Federal Law (Public Law 95-46)[b]	Authorizes study of problems related to completion of San Luis Drain
1977	USBR[b]	Asks USEPA about requirements for a waste discharge permit for San Luis Drain
1979	USBR and California water agencies[a,b]	Issues study of alternatives and final report recommending construction of drain; issues First Stage Environmental Impact Report for discharge at Suisun Bay (Chipps Island)
1981	USBR[a,b]	Begins drainwater flow into Kesterson Reservoir; begins San Luis Special Study to fulfill state requirements for obtaining a permit for discharge of drainage to the Bay-Delta at Chipps Island
1983	USFWS	Advises USBR of bird deformities/deaths at Kesterson National Wildlife Refuge
1984	USFWS and USGS[b]	Studies show environmental damage from selenium at Kesterson National Wildlife Refuge
1985	Secretary of the USDOI and California Governor[a]	Establish Federal-State San Joaquin Valley Drainage Program to conduct comprehensive studies to identify magnitude and sources of problem, the toxic effects of selenium on wildlife, and actions needed to resolve these issues
1985	Secretary of the USDOI	Orders cessation of discharge to Kesterson Reservoir and closure of San Luis Drain; initiates National Irrigation Water Quality Program to study effects of agricultural drainage on refuges across the western U.S.
1985	State Board	Issues order No. WQ85-1 for regulation of agricultural drainage to the San Joaquin River
1986	USBR	Closes San Luis Drain; issues Environmental Impact Statement for cleanup alternatives for Kesterson Reservoir
1986	Barcellos Judgment, U.S. District Court[a]	Calls for a Drainage Plan, Service Facilities, and a Drainage Trust Fund

Table 1. Chronology of authorizing, planning, regulatory, and evidentiary events for construction of a valley-wide drain or a San Luis Drain—Continued.

Date	Agency or Industry	Event
1987	Federal and State Interagency Committee[b]	Issues report of potential out-of-valley areas for disposal; due to environmental groups and coastal communities opposition, future studies limited to in-valley options
1988	USBR as ordered by State of California	Fills and grades Kesterson Reservoir as part of Kesterson Cleanup Program
1990	Federal and State Interagency Committee	Completes Drainage Management Plan for in-valley solutions to drainage problem
1991	Federal and State Interagency Committee	Forms Drainage Implementation Program and signs Memorandum of Understanding to help implement in-valley recommendations; Department of Water Resources is lead agency
1992	USBR[a]	As part of Barcellos Judgment, submits Draft Environmental Impact Statement for San Luis Unit Drainage Program; Environmental Impact Statement suggests in-valley approaches and stated *the social and environmental unacceptability* of completing a drain *precludes further consideration*; court rejects Environmental Impact Statement as not complying with judgment
1992	Federal Law 102-575 (CVPIA)	Calls for water allocations for the protection of fish and wildlife; and land retirement in the San Joaquin Valley
1993	U.S. House of Representatives (Subcommittee on Natural Resources)	Oversight Hearing on agricultural drainage issues in the Central Valley including reuse of a portion of the San Luis Drain by Grassland Area Farmers
1993	Porgans, Carter, USFWS, and environmental groups	Petition state over adequacy of Environmental Impact Statements for operation of privately owned drainage evaporation ponds where unavoidable bird loss was occurring
1994	Wanger Decision, U.S. District Court[a,b]	Decides to send the salty water north; calls for initiation of process to obtain a discharge permit for the San Luis Drain to the Bay-Delta
1995	USBR; Contra Costa County and others	Appeals Wanger decision; environmental groups intervene; decision pending
1995–96	USBR and San Luis Delta-Mendota Water Authority	Issues Environmental Assessment for reuse of the San Luis Drain by Grassland subarea; 28-miles of the San Luis Drain reopens to convey drainage to the San Joaquin River
1996	State Board[a]	State re-emphasizes that valley-wide drain is best technical and feasible solution for water quality and salt balance in the San Joaquin Valley, but calls for National Pollutant Discharge Elimination System permit
1997	Department of Water Resources	Starts preparing update of Drainage Management Plan due to non-implementation
1999	Department of Water Resources	Declares Drainage Management Plan to have been unsuccessful
1999	USBR, Department of Water Resources, and State Water Rights Decision 1641[a,b]	Recommend completion of the San Luis Drain to Bay-Delta or other out-of-valley alternative; call for Memorandum of Understanding to initiate environmental review for consideration of discharge application for the San Luis Drain
1999	U.S. House of Representatives	Field hearing to examine agricultural drainage issues including completing San Luis Drain
2000	Hug, and others, 2000, U.S. Court of Appeals	Reverses previous decision to compel USBR to build a drain to Bay-Delta, but rules USBR has duty to provide drainage service; drainage plan pending
2000	USBR	Initiates a process for providing drainage service to the San Luis Drain
2000	CALFED	Issues Programmatic Record of Decision for 30-year plan of Bay-Delta restoration and management
2005	USBR	Issues Draft Environmental Impact Statement on the San Luis Drainage Feature Re-Evaluation
2005	USBR	Issues Draft Environmental Impact Statement for renewal of long term San Luis Unit contracts independent of drainage considerations

[a] Recommendation for completion of drainage facility (i.e., San Luis Drain).

[b] Call for environmental review or notice of environmental concerns; CVP includes the San Luis and Delta-Mendota Service Areas.

Table 2. Chronology of investigative and regulatory events concerning selenium for the San Francisco Bay-Delta.

[Compiled with assistance of Khalil Abu-Saba, San Francisco Bay Regional Water Quality Control Board, and Kim Taylor, formerly with San Francisco Bay Regional Water Quality Control Board and now with the U.S. Geological Survey, Sacramento CA.]

Date	Agency, industry, or reference	Event
1975	Report to Association of Bay Area Governments (regional monitoring program, Risebrough and others, 1977)	Samples of transplanted *Mytilus edulis* show some of highest concentrations in Carquinez Strait
1982, 1985	USFWS	Elevated selenium concentrations found in scoter and scaup from South and North Bay
1985	State Board	Initiates 5-year *Selenium Verification Study* for intensive sampling of biota in areas of concern including Bay-Delta and San Joaquin River
1985–86	USGS and USBR	Samples of *Corbicula fluminea* and *Macoma balthica* show enrichment in North Bay
1986	Department of Water Resources and Cutter (1989)	Sampling shows internal sources of selenium from oil refineries in the mid-estuary
1986	Department of Water Resources and USGS	Invasion of the Asian clam in Suisun Bay changes benthic macroinvertebrate community
1986–1991	Department of Fish and Game and USFWS	As part of *Selenium Verification Study*, sampling shows elevated levels of selenium in scoter, scaup, white sturgeon, starry flounder, crab and shrimp
1986	Department of Health Services/Office of Environmental Health Hazard Assessment	Issues human health advisory for consumption of waterfowl (scaup and scoter) for Bay
1987–1988	Department of Water Resources; Cutter and San Diego-McGlone (1990)	Sampling shows anthropogenic selenium source is 52 to 92 percent of total selenium
1988	San Francisco Bay Board	Directs oil refineries to investigate selenium; crude oils from the San Joaquin Valley are targeted as source; calls for selenium control technologies rather than best management practices for waste streams
1988	Department of Health Services/Office of Environmental Health Hazard Assessment	Reaffirms human health advisory for consumption of waterfowl (scaup and scoter) and extends it to entire estuary
1988	USEPA	Establishes San Francisco Estuary Project as part of National Estuary Program
1988–1989	San Francisco Bay Board	Because water-quality standards not met in the North Bay, requests comprehensive conservation and management plan by 1992
1989	USEPA	Because of bioaccumlation in predators, overrules regional board and places North Bay on 304(l) list as substantially impaired by point sources of selenium; mandates control strategies to be implemented to reduce loads resulting in standards being met within 3 yrs
1991	San Francisco Bay Board	Issues selenium mass limits in National Pollutant Discharge Elimination System permits maximum limit for daily concentration is 50 µg/L
1991–1992	USEPA's National Estuary Program and San Francisco Estuary Project	Issues series of reports on status of pollutants, wildlife, wetlands, and aquatic resources of Bay-Delta
1992	USEPA	Promulgates 5 µg/L selenium standard for Bay-Delta because salt water objective of 71 µg/L selenium is underprotective
1992	USGS	Modeling studies show importance of phytoplankton-particulate-bivalve foodweb to predator tissues selenium concentrations
1992	Oil refiners	Appeal permits and sue regional board
1992	USEPA	Promulgates 5 µg/L selenium guideline in National Toxics Rule
1992	San Francisco Bay Board	Proposes Basin Plan Amendment that takes iterative mass reduction approach
1993	San Francisco Bay Board	Settlement agreement and issuance of cease and desist order for non-compliance of mass reductions
1993	USEPA's National Estuary Program and San Francisco Estuary Project	Workbook on Comprehensive Conservation and Management Plan for the Bay-Delta

Table 2. Chronology of investigative and regulatory events concerning selenium for the San Francisco Bay-Delta—Continued.

Date	Agency or Industry	Event
1993 to present	Oil refiners	Research and implement selenium reduction technologies on mandated time schedule
1993 and 1994	San Francisco Estuary Institute	Issues annual report on regional monitoring program for trace substances
1994	San Francisco Bay Board and oil refiners	Mandated avian risk study showed elevated concentrations in avian eggs and embryo deformities in Chevron marsh, a constructed wetland receiving oil refinery effluent
1995–1996	USGS and Interagency Ecological Program for the Sacramento-San Joaquin Estuary	Sampling in North Bay shows elevated selenium concentrations in *Potamocorbula amurensis*
1996	USFWS	Issues recovery plan for Sacramento/San Joaquin Delta native fishes
1998–2000	CALFED	Ecosystem Restoration Plan for Bay-Delta
1998, amended in 2000	USEPA in consultation with USFWS	Issues California Toxics Rule withholding rule on selenium
1998	San Francisco Bay Board and Oil Refiners	Scheduled to meet load reductions
1999	USEPA's National Estuary Program and San Francisco Estuary Project	Report on Comprehensive Conservation and Management Plan for the Bay-Delta
2000	State Board	Lists Bay-Delta as toxic hot spot

leaving productive saltwater waterbodies unprotected based on the current knowledge of selenium effects (USEPA, 2005). Criteria to specifically protect wildlife, although called for in 1989, have not been promulgated (USEPA, 1989 and 2005).

b. The USEPA criterion for the protection of aquatic life (5 µg/L selenium) is not in effect for upstream inflows to the Bay-Delta (the San Joaquin River and its tributary sloughs) due to State postponements of compliance until 2010 (USEPA, 1992; Central Valley Board, 1996d). Selenium concentrations in the San Joaquin River have exceeded USEPA criteria 50 percent of the time for the period 1987 to 1997 at Crows Landing (figs. 3 and 4) (Central Valley Board, 1996a, b, 1998f). Load limits enacted by the State in 1996 were exceeded in 1996 through 1998. Although called for in 1985, a comprehensive study of the effects of selenium on the San Joaquin River system has not been completed (State Board, 1985; Presser and others, 1996; Presser and Piper, 1998). An aquatic hazard assessment of a tributary slough receiving the greatest effect from agricultural drainage found the selenium hazard as *high* (Lemly, 1995, 1996a; USBR and others, 1998 and ongoing). Replacement of native species in the San Joaquin River has led to a rating of *poor* on the index of biological integrity (Moyle and others, 1986) for river sites above and below drainage discharges. Populations of fish in the San Joaquin River and adjacent sloughs are now dominated by introduced species having broad environmental tolerances (USBR and others, 1998 and ongoing). The role of selenium in these changes is not proven, but effects on native fish populations are documented elsewhere (see, for example, Lemly, 1997b; Hamilton, 1998, 1999).

c. Refinery discharges of selenium to the Bay-Delta have declined since 1998. State waste discharge permits now limit oil refinery effluents based on selenium loads (table 2). Effluents, however, are permitted to reach a daily maximum of 50 µg/L selenium, which is tenfold above the USEPA criterion (San Francisco Bay Board, 1992b; USEPA, 1987, 1992). It is expected that food web contamination attributable to the refineries will decline; however, dilution of the effluent discharges by low selenium inflows is critical. In 1995, deformed embryos were found in 30 percent of mallard (*Anas platyrhynchos*) nests and in 10 percent of American coot (*Fulica americana*) nests at a marsh used for selenium remediation in the North Bay receiving refinery effluent (20 µg/L selenium inflow into the constructed wetland and 5 µg/L selenium outflow) (Skorupa, 1998a).

d. Selenium concentrations were below recommended water quality protection guidelines (2 to 5 µg/L) in both the Delta and the Bay in all surveys of the Bay-Delta from 1982 to the mid-1990s (Cutter, 1989; Cutter and San Diego-McGlone, 1990; Cutter and Cutter, 2004). Nevertheless, selenium in the food web was sufficient to be a threat to some species and a concern to human health if those species were consumed (Department of Fish and Game, 1988 and ongoing; Fan and others, 1988; Drainage Program, 1990b; San Francisco Bay Board, 1992a, b).

e. A biological opinion and formal consultation by the USFWS and NMFS (1998 and amended, 2000) for 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 selenium jeopardizes several Bay-Delta or San Joaquin River fish [Delta smelt (*Hypomesus transpacificus*), Sacramento splittail (*P. macrolepidotus*), steelhead trout (*Oncorhynchus mykiss*) and chinook salmon (*Oncorhynchus tshawytscha*]; 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 and 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/L chronic selenium 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.

f. State permits for selenium discharges to private evaporation ponds used for agricultural drainage disposal in the southern San Joaquin Valley are limited to a selenium hazardous waste criterion of 1,000 µg/L (California Code of Regulations, 1979 and as amended). The southern San Joaquin Valley, including the Tulare Basin, is 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 (Department of Fish and Game, 1987; Drainage Program, 1989, 1990b). A 10 to 50 percent rate of embryo teratogenesis was documented during the period 1987 to 1990, causing the closure of most ponds (Skorupa, 1998a, b). An attempt to regulate evaporation ponds on the basis of field observations of effects to birds was not adopted in lieu of altering remaining drainage evaporation ponds to limit bird-use (*bird-free* ponds) and of providing compensatory and alternative wetland habitats (State Board, 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 percent) was the highest ever reported (Skorupa, 1998a).

g. Discharges to more recently constructed solar or accelerated evaporation ponds (*integrated on-farm drainage management systems*) are under even less restriction than traditional evaporation ponds, not needing to meet a hazardous waste code for selenium (California Code of Regulations, 2003).

h. Federal (40 CFR 131.12) and State (Central Valley Board, 1994a, 1996a) anti-degradation regulations may apply to impaired water quality segments of the San Joaquin River or the ground water aquifers of the San Joaquin Valley, but these rules have not been enforced. In addition to the degradation of the San Joaquin River noted above, mobilization of selenium by irrigation and contamination of ground water have resulted in concentrations of selenium > 1,000 µg/L selenium (a hazardous waste; California Code of Regulations, 1979 and as amended) in some aquifer locations in the San Joaquin Valley (Deverel and others, 1984; Gilliom and others, 1989).

7. Human health advisories against consuming selenium-contaminated edible tissue of fish [bluegill (*Lepomis macrochirus*) and largemouth bass (*Micropterus salmodes*)] and birds (ducks and coots) are presently posted for the San Joaquin Valley (Department of Fish and Game, 1985 and ongoing; 1986 and ongoing; Fan and others, 1988; Drainage Program, 1990b). Advisories also exist for consuming birds (scoter and scaup) from the Bay-Delta (Department of Fish and Game, 1988 and ongoing). The advisories are issued when selenium concentrations in flesh reach or exceed 2 µg/g wet weight (8 µg/g dry weight, assuming 75 percent moisture) (Drainage Program, 1990b; Saiki and others, 1991) and restrict consumption to not exceed 112 grams of flesh per two-week period or 20 grams of fish or bird muscle per day in addition to the regular daily intake (Fan and others, 1988). Children and pregnant women are advised not to consume any fish or game from the posted areas of contaminated ecosystems and landscapes.

8. Important gaps occur in existing knowledge (Luoma and Fisher, 1997; Clements, 2000; Presser and Piper, 1998). Most selenium studies have taken place in freshwater wetlands and reservoirs, but many of the processes and mechanisms that determine selenium effects can be applied generically. There is a deficit of knowledge about the fate and effects of selenium in estuarine and ocean environments similar to the Bay-Delta and Pacific Ocean, and important data gaps exist for specific regions of 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 selenium than for many other contaminants.

9. Comprehensive implementation of the Drainage Program's management components to help control drainage in contributing watersheds did not take place (Drainage Implementation Program, 1998). Drainage Program goals for San Joaquin Valley fish and wildlife protection were left unmet, although some wetland channel and evapora-

tion pond protection (a 2 µg/L objective) has been enacted (Central Valley Board, 1998b). The Drainage Program's broadly shared effort to sustain agriculture through (1) reduction of the amount of drainage water; (2) placement of remaining water under control; and (3) containment and isolation of selenium were thought able to largely correct waterlogging of farmland and reduce adverse impacts on fish and wildlife. These recommended in-valley actions, which provide a regional drainage infrastructure, also would be necessary for any eventual export of salt from the valley (Drainage Program, 1990a).

This report primarily:

- presents selenium issues and their history in the San Joaquin Valley, the San Joaquin River, and the Bay-Delta;
- projects potential loads of selenium from the western San Joaquin Valley based on engineering solutions and management alternatives proposed historically;
- details the state of knowledge of processes that determine the fate and effects of selenium released to the Bay-Delta;
- summarizes existing knowledge concerning selenium contamination in the Bay-Delta ecosystem;
- characterizes existing knowledge for each set of processes that link loads and effects;
- forecasts concentrations, form, bioaccumulation, trophic transfer, and effects of selenium on predators under various load scenarios; and
- defines research needs and actions that might help narrow the uncertainties about proposed discharges of selenium to aquatic ecosystems.

Selenium discharges to the Bay-Delta are changing, or could be changed, by activities expected to occur within the Bay-Delta and in the San Joaquin River/San Joaquin Valley 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.

Changing Selenium Issues

The probability is high in the future that discharges of selenium will increase to the Bay-Delta. A proposed 100-mile extension of the existing San Luis Drain would convey subsurface agricultural drainage from the western San Joaquin Valley to a discharge point near Chipps Island in Suisun Bay (figs. 3 and 4). The drain extension would help alleviate the build-up of salt and selenium in agricultural soils and the aquifers of the valley by exporting them from the valley and disposing of them in the Bay-Delta.

Existing policies for the western San Joaquin Valley are probably not sustainable (Wanger, 1994; Stevens and Bensing, 1994; State Board, 1997a, 1999a, d; Westlands Water District, 1996, 1998; U.S. House of Representatives, 1999; Hug and others, 2000). In general, soil and ground water quality are deteriorating in undrained lands and storage of salt and selenium is occurring in surface management areas and aquifers of the western San Joaquin Valley (Drainage Implementation Program, 1998). Disposal sites of sufficient scale for collected drainage (such as at Kesterson National Wildlife Refuge and Tulare Basin evaporation ponds) have resulted in adverse ecological effects. Disposal options for drainage have long been discussed, environmental impact reports prepared, and engineering studies of the problem made (table 1), but no systematic regional solution to the drainage problem, although proposed in 1990, has been implemented. Drainage problems continue to grow and to affect both agriculture and ecosystems [see, for example, USBR, 1962; California Department of Water Resources (Department of Water Resources), 1965a, b, 1969, and 1974; USBR, 1978; San Joaquin Valley Interagency Drainage Program (Interagency Drainage Program), 1979a, b; Brown and Caldwell, 1986; Drainage Program, 1990a; Drainage Implementation Program, 1998). As discussed later in more detail (also see appendix A), drainage disposal studies have provided insufficiently holistic evaluations of the problem. These studies have not comprehensively assessed (1) the ongoing affect of management actions aimed at more storage and less leaching; (2) ecological effects of agricultural drainwater disposal on receiving-water food webs and higher trophic level predators; and (3) the stressed and degraded nature of existing ecosystems.

Salinization and selenium contamination issues in the western San Joaquin Valley ultimately stem from the geologic setting, an imbalance in the hydrologic cycle, and clay layers impeding drainage (Interagency Drainage Program, 1979a; CH2M HILL, 1988; Drainage Program, 1989, 1990a). High evaporation rates in the semi-arid climate cause salinization of valley soils. Accumulated salts are rich in selenium 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 selenium. Because of the nature of valley conditions, selenium is mainly oxidized to mobile selenate. (Presser and Ohlendorf, 1987). Where drainage has been halted, selenium is accumulating in the internal reservoir of ground water in the San Joaquin Valley (Drainage Program, 1990a; Drainage Implementation Program, 1998; Westlands Water District, 1996, 1998). The accumulation of salts and contaminants in ground water will eventually impede beneficial use of this resource (State Board, 1985, 1987, 1994, 1999a, d; Central Valley Board, 1988, 1996a, 1998b). Where drainage water is being collected, its disposal results in increases in selenium contamination of surface water resources, with possible effects on ecological integrity (see mandated environmental reviews for proposed San Luis Drain in 1965, 1975, 1977, 1979, 1981, 1984, 1985, 1987, 1991, 1994, and 1999 listed in table 1). No feasible engineering solutions yet exist for treating irrigation drainage to remove selenium from the water-column, at least not at the scale necessary to alleviate the problem of waste disposal in the San Joaquin Valley (Hanna and others, 1990; Drainage Program, 1990a; Drainage Implementation Program, 1999a).

The State continues in their belief that the best solution to salt buildup in the San Joaquin Valley is out-of-basin disposal (table 1). This action is an effort to seek relief for California farmers. As in earlier proposals, the final point of discharge of this drain is the Bay-Delta. The State asserts that ultimately if salt is not removed from the basin, it will continue to impact water quality (State Board, 1999a; Central Valley Board, 1998b). The State, with final approval from USEPA, would be responsible for permit applications and environmental documentation for a master drain (an extension of the San Luis Drain) to remove salts from the western San Joaquin Valley.

On the Federal level, the U.S. 9th Circuit Court of Appeals decision concluded that the USDOI must provide drainage service, but the agency had discretion to meet the court order with a plan other than an extension of the San Luis Drain (Hug and others, 2000). In response to this court order, a plan of action was adopted which culminated in issuance of a draft environmental statement that evaluated several alternatives for drainage relief, one of which is Bay-Delta discharge from an extension of the San Luis Drain (USBR, 2001a, 2001b, 2002a, 2005a). Significant adverse environmental effects to aquatic resources because of selenium bioaccumulation are predicted for all action alternatives of the proposed project. The USBR is continuing to balance resource values in order to designate a preferred alternative and to develop feasibility plans for action alternatives. The no-action alternative analysis (e.g., not providing drainage service) also predicts adverse effects to aquatic receptors related to changes in selenium bioaccumulation, mainly because of the magnitude of continuing irrigation supplies affecting seepage and migration of selenium into ecosystems.

Environmental groups and proposed recipients of drainage remain opposed to a drain alternative as a solution to drainage problems; rather, in-valley source control, water conservation, drainage reuse, and land retirement (cessation of irrigation in areas of elevated selenium concentrations in shallow ground water) is preferred (The Bay Institute and others, 2003). Environmental actions being pursued to help better manage water supplies and control drainage impacts in the San Joaquin Valley and Bay-Delta include efforts to (1) initiate tradable loads programs for non-point sources of selenium; (2) limit exports of Bay-Delta water; (3) restore San Joaquin River flows; (4) plan recovery of threatened and endangered species; and (5) monitor the ecological health of important ecosystems (Environmental Defense Fund, 1994; Save the Bay and others, 1998; Karlton, 2004; The Bay Institute, 2005).

The San Joaquin River is the only current means (that is, the only natural channel) by which selenium and salts can be removed from the San Joaquin Valley. Some agricultural drainage is currently discharged into the San Joaquin River (USBR, 1995 and 2001c; USBR and San Luis and Delta-Mendota Water Authority, 1995 and 2001), but inflows of selenium from the San Joaquin River to the Bay-Delta have traditionally been small compared to other sources (Cutter, 1989; Cutter and San Diego-McGlone, 1990; Johns and others, 1988). This is because although the San Joaquin River is hydrologically connected to the Bay-Delta, prior to the 1990s, the river was almost completely diverted and recycled back south to supply canals for agricultural and urban use before it reached the Bay-Delta (figs. 3 and 4). Hence, little selenium discharged to the river reached the Bay-Delta. Proposed management changes call for (1) less recycling of the river combined with alteration of flow patterns of the lower river to improve throughput to the Bay-Delta; and (2) increased flow to the river itself for restoration purposes. Changes in selenium discharges to the San Joaquin River will be manifested in downstream receiving waters (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.

Recent changes that could affect the quantity and quality of selenium discharges to the Bay-Delta and relevant regulations and policies that affect the interface of the San Joaquin River and Bay-Delta are summarized below (also see tables 1 and 2).

1. The 1994 Bay-Delta Water Accord (State Board, 1994) mandates greater inflows to the Bay-Delta from the San Joaquin River. In 1995, the CALFED Bay-Delta Program began to comprehensively address management and restoration in the estuary and watersheds. In 2000, a programmatic Record of Decision with a 30-year plan was issued (CALFED, 1998a, b; 1999a, b, c, d; 2000; 2005). Specific objectives include providing an environmental water account to benefit fish and habitats; installing fish screens and operable flow gates; increasing State Water Project diversions to 8,500 cubic feet per second (and eventually to 10,300 cubic feet per second); and increasing storage, conjunctive use, and conveyance.

2. A reduction in recycling of the San Joaquin River and an increase in drainage discharge from the San Joaquin Valley during seasons of elevated flows are strategies for slowing the salinization of agricultural soils (EA Engineering, Science, and Technology, 1999). Hence, a net increase or an increase during some months (during high flows) in selenium discharges to the San Joaquin River is possible in the future depending on river inflow and management scenarios.

3. A Federal agreement and a State permit adopted in 1995 and renewed in 2001 (Grassland Bypass Channel Project), specify conditions from WY 1997 through WY 2009 [a water year (WY) begins in October] for use of an existing 28-mile section of the San Luis Drain. Renamed the Grassland Bypass Channel, this drain conveys subsur-

face agricultural drainage to the San Joaquin River from approximately 100,000 acres in the northernmost area that requires drainage (USBR, 1995, 2001c; USBR and San Luis Delta-Mendota Water Authority, 1995 and 2002; USBR and others, 1998 and ongoing). This project is in response to listing of segments of the San Joaquin River by the State as impaired in water quality because of selenium. Even though agricultural drainage is considered non-point source pollution, tools to control sources and trade loads among drainage districts traditional to regulation of point-source pollution were applied to this agricultural area (EDF, 1994). Compliance with USEPA's 5-µg/L selenium criterion for the upper San Joaquin River is scheduled for October 2010, based on decreasing selenium and salt load targets for agricultural discharges. Other project allowances include (1) management alternatives store some salts and selenium in surface management areas and in aquifers; (2) uncontrolled discharge of stored drainage is permitted under periods of wet weather; and (3) degradation of a tributary of the San Joaquin River (Mud Slough) that connects the San Luis Drain to the river is allowed until 2009. Drainage alternatives, such as to construct a pipe to directly drain to the river, are necessary by 2009 to address degradation of Mud Slough. Further assessment at that time will be conducted to determine overall drainage conditions in the western San Joaquin Valley and future management actions.

4. Real-time dilution of salt, boron, or dissolved oxygen could occur in portions of the San Joaquin River in response to State regulated objectives and USEPA regulation of non-point source pollution through TMDLs (Total Maximum Daily Loads) or TMMLs (Total Maximum Monthly Loads). This approach would change the amount and timing of selenium loading to the Bay-Delta (Central Valley Board, 1994b, 1996a, 1998a, 2000a; State Board, 1997a, 1999a; USEPA, 2000) as loads are integrated with flows.

5. Proposed restoration of the San Joaquin River includes increasing flows in the river to aid fish passage (Natural Resources Defense Council and others, 1988, 1989, 1992, 1999; CALFED, 1999a; URS Greiner Woodward Clyde, 2000).

6. A State water rights decision reinforces the need for the USBR to meet salinity objectives at Vernalis on the San Joaquin River and at three locations in the interior of the southern Delta (State Board, 1999a; EA Engineering, Science, and Technology, 1999). Salinity objectives adopted in 1991 were violated most months of the year (67 to 78 percent from 1986 to 1998). This state requirement would result in changes in flow management to help dilute salt discharges.

7. Construction of an isolated conveyance facility (similar to the peripheral-canal conveyance proposed in California in the 1980s, but rejected by voters) or modifications of current diversion and export channel dimensions could result in an exchange of Sacramento River inflow for San Joaquin River inflow to the Bay-Delta (CALFED, 1998a, b).

8. Reduction of selenium loads and changes in treatment technologies to meet goals set by the San Francisco Bay Board (1992a, b, 1993, 1996, 1997) (table 2) means that concentrations of at least some forms of selenium (specifically, selenite) in the Bay-Delta are decreasing (Cutter and Cutter, 2004).

9. Biogeochemical transformation pathways and bioavailability of selenium could change as predominant sources to the Bay-Delta change. Refinery selenium was dominated by selenite; selenium from the San Joaquin Valley is dominated by selenate, with some apparent conversions to organo-selenium in receiving waters (Cutter, 1989; Cutter and San Diego-McGlone, 1990; San Francisco Bay Board, 1992a, b, 1996, 1997).

10. 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 would 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 and others, 1985). Longer hydraulic residence times seem to be associated with greater selenium contamination in the food web (Lemly, 1997a; Zhang and Moore, 1997a; Skorupa, 1998a).

Biological changes also are occurring in the Bay-Delta ecosystem, and some of these appear to affect selenium cycling:

1. The dominant consumer organism in the Bay-Delta changed with the invasion of the Asian clam *P. amurensis* in 1986 (Nichols and others, 1986; Carlton and others, 1990; Brown and Luoma, 1995b). It is possible that this species is especially efficient at bioaccumulating selenium, although studies directly addressing the mechanisms of selenium bioaccumulation by *P. amurensis* are not yet complete (Brown and Luoma, 1995a; Luoma and Linville, 1997; Linville and others, 2002). 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 and others, 1989; Nichols and others, 1986).

2. One implicit goal of a successful estuary 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 casts doubt on the compatibility of existing or greater levels of selenium contamination with restoration goals.

3. The cause of the declines of some key species in the Bay-Delta (such as white sturgeon, Sacramento splittail, starry flounder, surf scoter) may include selenium effects on reproduction and ultimately, on survival of the population.

Increased selenium in the Bay-Delta could increase that threat.

4. Marsh restoration in the Bay-Delta, if accompanied by increased selenium discharges, could result in the trapping and recycling of increased quantities of selenium in the system, with the possibility of greater selenium contamination in some species. Under the worst scenarios, it is conceivable that management of the concomitant issues of water and salt rather than selenium contamination could create an ecological crisis in the Bay-Delta similar to that created at Kesterson National Wildlife Refuge in the 1980s.

Refinements of selenium water quality criteria, especially for the Bay-Delta, also are likely. The current USEPA criterion for the protection of aquatic life (5 µg/L) is based on bioaccumulation-related toxicity observed in Belews Lake and Hyco Reservoir (USEPA, 1987 and 1992). The USFWS recommended criterion (2 µg/L) is based on a series of case studies of selenium contamination and effects on birds in western wetlands (Skorupa, 1998a; USFWS and NMFS, 1998 and amended 2000). The Canadian criterion for wildlife protection (1 µg/L) is lower than both the current USEPA criterion and the recommended USFWS criterion (Environment Canada/Health Canada, 1995; Outridge and others, 1999). The technical limitations for the basis of existing and recommended water quality criteria raise questions about their suitability as the sole standard to assure protection of the Bay-Delta (Skorupa 1998b; Engberg and others, 1998; USEPA, 1989, 1998, 2005; USFWS and MNFS, 1998 and amended 2000; Reiley and others, 2003) (see previous discussion). As noted, selenium concentrations were below recommended guidelines in both the Delta and the Bay in the latest surveys in 1996. Nevertheless, selenium in the food web was sufficient to be a threat to some species and a concern to human health if those species were consumed (Linville and others, 2002; Department of Fish and Game, 1988 and ongoing; Fan and others, 1988; San Francisco Bay Board, 1992a, b) (table 2). The Bay-Delta is probably best suited for site-specific selenium guidelines, but the details of such guidelines have yet to be identified.

Given the dynamic nature of this debate, Federal and State agencies may be required to further evaluate proposals and discharge permits that could significantly change selenium inputs to the Bay-Delta. Particularly affected would be the San Joaquin River watershed, the south Delta, and the North Bay, which includes Suisun Bay, Carquinez Strait, and San Pablo Bay (fig. 3).

Approach to Understanding Changing Issues

Linked factors that determine effects of selenium on aquatic food webs and higher trophic levels are systematically described in this evaluation of selenium issues (Bay-Delta selenium model, fig. 2). The approach presented here differs from earlier attempts that skip links in tying waterborne selenium to its ecological effects (Stephan and others, 1985; USEPA, 1980, 1987, 1992, 1997 and amended 2000, 1998, 2005; USFWS and NMFS, 1998 and amended 2000; Reiley and others, 2003). This comprehensive approach offers opportunities to more accurately forecast ecological effects from loads and to identify resolutions of difficult questions involved in water, salt, and selenium management. Steps in the Bay-Delta selenium model are (fig. 2):

- **Developing loads scenarios from potential sources of selenium.** Selenium loads calculated from available concentration and drainage volume data provide the basis for upper and lower limits of selenium discharge that can be expected to enter the Bay-Delta. Analyzing the annual, monthly, daily, and hourly variability of selenium loading is necessary to address trends and patterns in discharges. The accuracy of selenium load calculations on any timescale is dependent on the number and frequency of the measurements used to determine flow and selenium concentration (Presser and others, 1996; Presser and Piper, 1998). Large uncertainties are associated with data compiled for annual average loads of selenium from agricultural, refining, 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 presented here, although documented as to source and type (see, for example, appendices A through D), should be used with caution and are applied here to obtain ranges of projected selenium loads.

- **Identifying implications of modes of conveyance that determine transport of selenium loads to the Bay-Delta.** A proposed San Luis Drain extension or the San Joaquin River are the most likely modes of conveyance from the San Joaquin Valley (fig. 3). If a San Luis Drain extension is constructed to Chipps Island in the Delta, selenium and salts from the soils of the San Joaquin Valley would be released directly into the Bay-Delta. During the period when studies of selenium were conducted in 1986 to 1990, the San Joaquin River was mostly recycled, so little selenium reached the Bay-Delta from this source. The passage of the San Joaquin River into and through the Delta is not well known at present, but hydrologic models exist that can be used as frameworks for future modeling (see, for example, Cheng and others, 1993; Monsen, 2000). Throughput of San Joaquin River flows into the Bay-Delta could be influenced by changes in water management to aid fish passage including construction of elaborate Delta barriers and scheduling of flushing flows.

- **Identifying effects of projected loads on concentrations in receiving waters**. Loads and seasonal variability in Sacramento River and San Joaquin River inflows are critical factors. Consideration of seasonal (six month low or high flow) and climatic (wet or dry year) effects enhance predictability. Evaluation on a monthly basis provides additional improvement in determining concentrations in the Bay-Delta.

- **Identifying changes in and implications of biogeochemical speciation of selenium and biogeochemical transformations of selenium between dissolved and particulate forms.** Speciation of selenium is critical in that it drives routes and efficiency of transformation of selenium from dissolved to particulate forms. Understanding particulate selenium and its speciation cycle is critical in determining biological effects.

- **Incorporating factors controlling bioavailability and biotransfer of selenium to macroinvertebrate primary consumers under different concentration and speciation conditions.** Pathway-specific bioaccumulation models consider (1) the form and concentration of particulate selenium; and (2) the physiology (ingestion and efflux rates) of prey organisms. Benthic food webs of the Bay-Delta result in more bioaccumulation than other food webs (Luoma and others, 1992; Stewart and others, 2004; Schlekat and others, 2004).

- **Determining exposure of sensitive predators from modeled selenium concentrations in invertebrate and vertebrate prey in the Bay-Delta ecosystem.** Existing data from 1988 to 1999 for selenium concentrations in bioindicator clams in the Bay-Delta show elevated concentrations compared to uncontaminated reference areas (Johns and others, 1988; Brown and Luoma, 1995a; Luoma and Linville, 1997; Linville and others, 2002). Exposure of predators is determined by the level of bioaccumulated selenium in these prey organisms (San Francisco Bay Board, 1992a, b, 1993, 1996, 1997).

- **Estimating effects of selenium 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 and others, 1985; Nichols and others, 1986; Davis and others, 1991; Harvey and others, 1992; Monroe and others, 1992; and USFWS, 1995). Many threatened species are not resident in the system all year, but some important species are vulnerable residents. Through 1996, both selenium concentrations in tissue of predators and in their food pointed to threats to the reproductive health of the predators (White and others, 1987, 1988, 1989; Cutter, 1989; Johns and others, 1988; Cutter and San Diego-McGlone, 1990; Urquhart and Regalado, 1991; San Francisco Estuary Project, 1991; 1992; San Francisco Bay Board, 1992a; b; Luoma and others, 1992; Brown and Luoma, 1995a; Luoma and Linville, 1997; Linville and others, 2002). However, such estimates of risk are derived from laboratory and field studies conducted elsewhere (USEPA, 1998; Lemly, 1993a, 1995, 1996a, 1998a; Skorupa, 1998a; Engberg and others, 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 of Selenium in the Bay-Delta

Major sources of selenium in the Bay-Delta are (figs. 3 and 4):

- discharges of irrigation drainage conveyed from agricultural lands of the western San Joaquin Valley into the San Joaquin River or potentially from an extension of the San Luis Drain;

- effluents from North Bay refineries which refine crude oil from the western San Joaquin Valley along with crude oil from other sources; and

- Sacramento River inflow which is the dominant freshwater contribution (high water volume) to the Bay-Delta.

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

Selenium from the Western San Joaquin Valley

The problem

The Coast Ranges, which border the San Joaquin Valley on the west, are composed of marine sedimentary rocks that are enriched in selenium (fig. 3; also see appendices A and B) (Presser and Ohlendorf, 1987; Presser and others, 1990). An internal reservoir of salt (and by inference selenium) has accumulated for 1.0 to 1.2 million years within the San Joaquin Valley 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 and others, 1989; Presser and others, 1990; Presser and others, 1994; Presser, 1994b) (see appendices for detailed analysis). The most selenium-rich region of the San Joaquin Valley is the Panoche Creek alluvial fan, which supports intensively irrigated land (Tidball and others, 1986, 1989). Salts and selenium buildup on soils as a result of both the arid climate (<10 inches of precipitation and >90 inches of evaporation) and poor drainage (clay layers impede downward movement of water causing water-logging of the root zone).

The San Joaquin Valley has a net negative annual water budget (evaporation exceeds precipitation). Prior to development of the water management system, a permanent shallow ground-water table only occurred in ground-water discharge zones near the trough of the San Joaquin Valley. 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 (see detailed discussion, appendix A).

Massive irrigation leaches salt and selenium and moves them into aquifers and surface waters. Installation of subsurface drains increases the speed, volume, and control of drainage of shallow ground water 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 San Joaquin Valley (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) (figs. 3 and 4). 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; Department of Water Resources, 1979 and 1982). Simple water and mass balance observations explain the attractiveness of an engineering solution that would increase salt and water discharge from the San Joaquin Valley.

Prediction of long-term reservoir: how sustainable is discharge

In planning for 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; 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 San Joaquin Valley. Managed volume of drainage discharge would increase over a hypothesized 100-year planning 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 San Luis Drain, showed a slowing in the rate of increase after 40 years (appendix A, fig. A3).

The geohydrologic balance of selenium (or salt) ultimately determines the degree of contamination build-up in the San Joaquin Valley (appendix A, tables A2 and A3). The primary geologic inventory of selenium in the Coast Ranges is the ultimate source of influx. Drainage from the San Joaquin Valley is the source of efflux, whether natural or artificially accelerated by engineering means. The internal labile reservoir of selenium in San Joaquin Valley is growing because the rate of removal of selenium-enriched salts from the valley is naturally slow. In general, calculations of the amounts of selenium in the reservoir within the Panoche Creek alluvial fan also confirm the massive nature of selenium accumulation in the San Joaquin Valley. Calculations based on two scenarios (appendix A, tables A2 and A3) show that no long-term reduction in selenium discharge would be expected for 63 to 304 years at the lower range of reservoir projections and assumed removal rate (42,785 pounds of selenium/year). Drainage of wastewaters outside of the San Joaquin Valley may slow the degradation of San Joaquin Valley resources, but drainage alone cannot alleviate the salt and selenium build-up in the San Joaquin Valley, at least within a century, even if influx of selenium from the Coast Ranges could be curtailed.

Several observations lead to further understanding of selenium source loads. On a current, yearly scale for selenium loads and concentrations from the western San Joaquin Valley: (1) the selenium load from the Panoche Creek upper watershed (137 pounds in January and February 1997; 8,045 pounds in February 1998, an exceptionally wet month) is a small percentage of a projected total annual load from the San Joaquin Valley (42,785 pounds assumed from all subareas); (2) 16 percent of the Panoche Creek selenium load (962 pounds) was in the dissolved fraction and 84 percent (5,033 pounds) was in the suspended fraction in February, 1998 (appendix A, table A3) (U.S. Geological Survey, 1999; Kratzer and others, 2003); (3) selenium concentrations in sediment samples from Panoche Creek were relatively low historically and remained so in 1998 (1 to 2 µg/g), thus depending on the large mass of sediment eroded during storms to accounts for the large fraction of suspended matter loading of selenium during runoff from large magnitude storms (appendix A, table A4) (Presser and others, 1990; (4) dissolved selenium concentrations 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 and others, 2003).

Selenium concentrations in source waters

The effect of the large reservoir of selenium calculated above can be seen in the quality of ground water in the western San Joaquin Valley (table 3). Extensive measurement and study of ground-water aquifers in the San Joaquin Valley have been made since 1917 (Mendenhall and others, 1916; Davis and Poland, 1957), but selenium concentration analyses were not a part of water quality studies until the

1980s (Presser and Barnes, 1984, 1985; Deverel and others, 1984; Drainage Program, 1989, 1990a). Selenium concentrations in shallow ground water surveyed in 1984 varied based on physiographic zone (alluvial fan, basin rim or basin trough) (Deverel and others, 1984). Average selenium concentrations in drainage sumps in the area of the Panoche Creek alluvial fan ranged from 140 to 4,200 µg/L (Presser and Barnes, 1985). These concentrations are reflective of shallow ground-water conditions as opposed to managed drainage, which may be blended. Studies in 1989 in the area of the Panoche Creek alluvial fan showed selenium concentrations ranged from 96 to 7,300 µg/L selenium in individual sump discharges or well samples at depths up to 50 ft below land surface in areas served by subsurface drains (Gilliom and others, 1989) (table 3). Selenium concentrations depend, in part, on the number of years the fields were drained. Concentrations of selenium in subsurface drain water in the area of sampled wells ranged from 400 to 1,000 µg/L. A more recent compilation used in the evidentiary process (Wanger, 1994; Stevens and Bensing, 1994; Westlands Water District, 1996) and in regulatory planning showed concentrations in shallow ground water ranged from 75 to 277 µg/L selenium (range of means) (Drainage Program, 1990a; Central Valley Board, 1996c, d) (table 3). Data presented in testimony and by the State projected an

Table 3. Selenium concentrations in shallow ground water and subsurface drainage in Westlands Water District, Grassland Drainage Problem Area, Tulare subarea, and Kern subarea.

Source and Sampling	Selenium (µg/L)	
San Luis Drain and agricultural sumps (State Board, 1985; Presser and Barnes, 1985)		
San Luis Drain, discharge (1983–84)	330–430	
San Luis Drain discharge, 1984	340	
Westlands subarea drainage sumps	140–1,400	
Grassland subarea drainage sumps	8–4,200	
Westlands subarea (Stevens and Bensing, 1994; Wanger, 1994; Westlands Water District, 1996)		
San Luis Drain discharge (1981–84)	230–350	
Westlands Water District drainage (from USGS data dependent on grid size)	208–277 (range of means)	
Westlands Water District drainage estimate	300	
Westlands Water District drainage (63 sites within 42,000 drained acres, 1993)	163 (mean)	
Westlands Water District estimate of drainage with treatment	50	
USBR (conservative estimate)	at least 150 ppb	
Grassland Drainage Problem Area (Central Valley Board, 1996a,b; Drainage Program, 1990)		
Subsurface tile drainage estimate	150	
Subsurface tile drainage modeling estimate	120	
Subsurface drainage sumps (annual survey)	211 (mean); 134 (median)	
Model of estimated of drainage problem area (effluent surface plus subsurface)	80 (average)	
Estimated subsurface discharge to San Joaquin River for 1990	150	
Estimated subsurface discharge to San Joaquin River for 2040	75	
Panoche Creek alluvial fan (Grassland and Westlands subareas) (Gilliom and others, 1989)		
Murietta field well (10–15 feet)	320–7,300	
Murietta field subsurface drains	800–1,000	
Wells associated with agricultural field drained for 15 years (10–15 feet)	96–1,000	
Subsurface drains associated with agricultural field drained for 15 years	400	
Tulare and Kern Basins evaporation ponds (1988 and 1989) (Central Valley Board, 1990 a, b)		
Inflows to evaporation ponds	<1–760	
Evaporation ponds	<1–6,300	
Tulare and Kern subareas observation wells (12–25 feet) (Fujii and Swain, 1995)		
Alluvial fan zone	(median)	(maximum)
West-side alluvium	8	520
East-side alluvium	< 1	25
Basin zone		
West-side basin	3	240
East-side basin	< 1	320
Tulare Lake Zone		
Northeastern margin	< 1	4
Southern/western margin	34	1,000
Lake bed	< 1	2

average concentration of selenium in shallow ground water and hence, subsurface drainage, of at least 150 µg/L selenium in the farming areas affected by the Panoche Creek alluvial fan (table 3).

Distribution of selenium and selenium concentrations in shallow ground waters of southern San Joaquin Valley (Tulare and Kern subareas, figs. 3 and 4) vary based on (1) sources of sediment (Coast Range or Sierra Nevada); (2) location within depositional zones (alluvial fan, basin trough, or lake bed); and (3) depositional environment (oxidation or reducing) (Fujii and Swain, 1995) (table 3). The median selenium concentration in the most affected areas in the southwestern margin of the lake zone was 34 µg/L, with a maximum concentration of 1,000 µg/L selenium in that area. Selenium concentrations measured in drainage discharges to evaporation ponds from 1988 to 1997 also reflect shallow groundwater conditions (table 3 and detailed in appendix B, tables B19 through B21). Most selenium concentrations in currently regulated discharges to evaporation ponds in the southern San Joaquin Valley are above those associated with avian risk, and consequently dischargers are required to provide mitigation and alternative habitat (State Board, 1996c).

Most selenium concentrations in shallow ground water listed in table 3 are above the concentration presently regulated as the maximum for oil refinery effluent (50 µg/L) and above the concentration estimated that is possible with treatment (50 µg/L) (Westlands Water District, 1996).

The effect of a large reservoir of selenium on recent subsurface drainage flow and quality (fig. 5) is generalized from data collected during frequent sampling of drainage source water (current agricultural discharges to the San Joaquin River in WYs 1997 and 1998 from the Grassland subarea, see appendix A, figs A7 to A10; appendix B, tables B9 and B10; and appendix D) (USBR and others, 1998 and ongoing). Selenium concentration in source agricultural drainage is not diluted when outflow or volume of drainage increases, except in extreme precipitation events. Rather, when considering selenium source waters as opposed to receiving waters, increasing input of applied water results in increased selenium concentrations and output loads, indicating massive selenium storage that is now subject to transport. Additionally, testimony in State water rights hearings reaffirm that the action of massive irrigation supply (mainly from the Federal Central Valley Project) is a principal cause of the discharge of salinity, and hence, the cause of violations of water quality objectives for salinity for the Bay-Delta (State Board, 1999a).

Removal of salt (and selenium) also is slowed by the recycling of the San Joaquin River. The San Joaquin River can be almost completely diverted back into the San Joaquin Valley, with little river flow entering 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) (fig. 4). Recycled San Joaquin River water is applied again in the Northern and Grassland subareas as irrigation (fig. 3). The degree of recycling is determined by water management. Water management began changing toward less recycling in 1994 and direct throughput of the San Joaquin River may increase in the years ahead to help restore San Joaquin River fish and fish habitat. A reduction in recycling and an increase in drainage discharge during seasons of elevated flows are proposed strategies for slowing the salinization of agricultural soils. However, management to meet all goals including salinity standards for the San Joaquin River at Vernalis is complex. Strategies may include constructing storage or holding ponds to optimize timed release of drainage. Agricultural drainage discharges currently are not, in general, coordinated with periods of high river flows (appendix A, fig. A11).

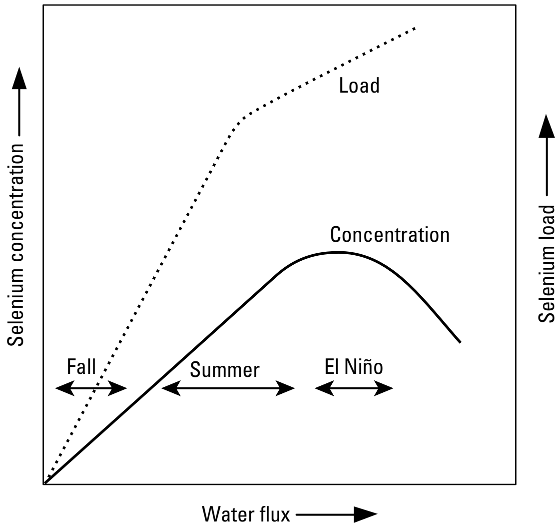

Figure 5. Schematic of selenium concentration in drainage (source waters) as a function of flow (water flux) and resultant selenium load illustrating the effect of a large reservoir of selenium on the quality of subsurface drainage.

Drainage management: history

Management plans have considered *in-valley* and *out-of-valley* drainage alternatives. *Out-of-valley* solutions mean export of the salt-laden drainage (and its selenium load) to somewhere else. The most frequently mentioned of these solutions is an extension of the San Luis Drain with discharge to the Bay-Delta. *In-valley* solutions imply local storage and treatment of selenium-rich drainage. However, satisfactory treatment technologies have not yet been demonstrated and storage does not seem sustainable (see previous discussion and Drainage Program, 1990a).

Planning for a drain to carry salt-laden irrigation return water (and the accompanying selenium) from the San Joaquin Valley began in 1955 (table 1). An 85-mile section of the San Luis Drain was completed in 1975, to collect irrigation drainage water from one section of the valley, the Westlands Water District (figs. 3 and 4, Westlands subarea). The San

Luis Drain began discharging concentrated drainage water in 1981 to Kesterson National Wildlife Refuge (figs. 3 and 4), 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 12 ponds. Subsequent monitoring revealed a contaminated ecosystem with elevated concentrations of selenium throughout sampled water, sediment, plants, and invertebrates (Saiki and Lowe, 1987). Avian deformities were ultimately linked to selenium exposure from food web contamination (Ohlendorf and others, 1986; Presser and Ohlendorf, 1987). The San Luis Drain 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 selenium concentrations persist in the remediated terrestrial ecosystem at Kesterson Reservoir (CH2M HILL, 1996, 1997, 1999a, b; Presser and Piper, 1998).

Management of selenium currently differs among regions (subareas) in the San Joaquin Valley. Five subareas (Westlands, Tulare, Kern, Grassland, and Northern) of the western San Joaquin Valley were designated based on hydrologic and geologic features and on options for management of irrigation and agricultural wastewater discharge (Drainage Program, 1990a) (fig. 3). Selenium-laden wastewater is recycled or stored in groundwater aquifers in the Westlands subarea. In the Tulare and Kern subareas, drainage is collected in privately owned evaporation ponds located on farms. Reproductive effects in aquatic birds were observed in some of these ponds and associated wetlands (Skorupa, 1998a). Drainage from the Grassland subarea prior to 1995 was discharged into canals, sloughs, and wetlands that eventually flowed into the San Joaquin River (fig. 3). Implemented in 1995, the Grassland Bypass Channel Project collects drainage under permit from the Grassland subarea and transports it through an existing 28-mile section of the San Luis Drain to Mud Slough, a tributary of the San Joaquin River (USBR, 1995; 2001c; USBR and San Luis Delta-Mendota Water Authority, 1995 and 2002; USBR and others, 1998 and ongoing) (fig. 3; appendix B)**.** Most estimates suggest that drainage needs for the Northern subarea are relatively small compared to other areas, although conditions and estimates of acres requiring drainage have not been updated since 1990.

Selenium loads: general considerations

The problem of progressive soil salinization and the build-up of groundwater contamination could require collection of drainage from larger and larger areas of the San Joaquin Valley if agricultural activities continue and a drainage outlet is available to help alleviate annual imbalances. A realistic, long-term evaluation of the potential for selenium discharge must fully consider both the present and the future extent of the problem (appendix B).

Identification and classification of *problem lands* in the San Joaquin Valley took place as early as 1930 (Ogden, 1988). Since the 1950s, technical studies have estimated the extent of the acreage requiring drainage under varying conditions of water import, water export, salinity, and ground-water 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 Central Valley Project 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 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* (Drainage Program, 1989). Between 1985 and 1990, the joint Federal/State program (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 effects on agriculture or aquatic resources) (appendix B). The program developed an *in-valley* management plan for the next 50 years for agricultural subsurface drainage with specific management alternatives (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 ground-water conditions and the annual salt build-up that eventually limit the uses of valley lands and ground water. The Drainage Program's regional studies and data provide much of the information used in the assessment of loads presented here for subareas of the San Joaquin Valley (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 selenium 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 Drainage Program. Recommendations for treatment techniques were not included because success of technology on a large-scale was not proven as of 1990 (Drainage Program, 1990a). Implementation of the management plan was only partial and systematic monitoring and data analysis has not yet occurred (Drainage Implementation Program, 1998).

The Drainage Program (1990a) management plan estimated a *problem area* of 444,000 acres would create 314,000 acre-ft 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-ft by year 2040. For these estimates of acreage, the 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 (lands with an actual drainage problem). The 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 ft of land surface*. Using this criterion, estimates ranged from 765,000 acres in 1990, to 918,000 acres in year 2000, to 1,057,000 acres in year 2040. Using a criterion *of lands contributing the largest percentage of selenium to drainage discharge* (that is, lands overlying areas of shallow ground water with selenium concentrations of > 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 Drainage Program management plan was not implemented. Land retirement recommended by the Drainage Program by 2000 was 21,000 acres and by 2040, was 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 (in table 1, those for 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 rights hearings, the total acreage of lands affected by rising water tables and increasing salinity is about 1,000,000 acres in the San Joaquin Valley (State Board, 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 (USDOI Interagency Land Retirement Team, 1999; Drainage Implementation Program, 1999b).

Factors in calculating selenium loads

One approach to calculating selenium loads is to examine historical records and planning efforts for agricultural discharges with the goal of developing relations among acreage, drainage generated or discharged, selenium concentration, and load of selenium. Selenium load scenarios in this report are developed from historical annualized drainage volumes and assigned concentrations reflective of compiled measured concentrations in ground water and drainage 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 selenium distribution or 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 selenium loads involves three factors (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 the context of this report, 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 the analysis presented here, the distinction made between *problem water* and subsurface drainage helps in projecting 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-ft per acre per year (Drainage Program, 1990a). The Drainage Program predicted that changes in on-farm drainage management practices could reduce the volume generated to approximately 0.4 acre-ft 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-ft per year (appendix B, table B8). An average annual *pollution abatement objective* of 0.2 acre-ft per acre per year has been considered as necessary to meet selenium load limits in the Grassland subarea (Environmental Defense Fund, 1994).
- **The concentration of selenium in irrigation drainage.** Reconnaissance-level data on selenium concentrations in shallow ground waters are available from all areas except the Northern subarea (also see appendices A through D for details) (Drainage Program, 1989, 1990a) (table 3). The concentration of selenium in effluent drainage reflects a managed balance of input, output, and storage. Treatment technologies (mostly unspecified) or dilution with selenium-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 selenium (for example, Drainage Program, 1990a).

All three factors can vary greatly depending upon assumptions about management strategies. Two possible alternative management *futures* were defined by Drainage Program: (1) no implementation of the Drainage Program management plan, 0.60 to 0.75 acre-ft per acre per year generated drainage, namely, *without future*; and (2) with implementation of the Drainage Program management plan, 0.40 acre-ft per acre per year generated drainage, namely, *with future* (Drainage Program 1989, 1990a). A third condition defined for use in load scenarios presented here is called *with targeted future*. The *targeted future* condition applies a factor of 0.20 acre-ft 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 Drainage

Program plan was implemented, the amount of drainage would be reduced to 0.4 acre-ft per acre per year, but the total land in production would be preserved.

A mixture of metric and English units is used in selenium load calculations provided here and in the following discussion. This is unconventional for a scientific report, but is done here to aid communication with the widest audience in the most recognizable terms. Loads of selenium are expressed in pounds (lbs); area is described in acres; volume of discharge is expressed in acre-feet (acre-ft) or million acre-ft; selenium concentrations are expressed as μg/L (equivalent to the regulatory term parts per billion) or μg/g (equivalent to the regulatory term parts per million). Conversion between these units and other scientific units, which are used in the analysis of selenium ecological effects, can be found in table 4. Selenium (Se) load in lbs is calculated using the equation:

[Se concentration (μg/L) × volume of drainage (acre-ft)]
× 0.00272 = Se load (lbs),
or
[Se concentration (μg/L) × [(acres) × (acre-ft per acre)]
× 0.00272 = Se load (lbs),

where 0.00272 lbs Se per acre-foot is equal to a concentration of 1 μg/L Se in an acre-foot of water.

Table 4. Conversion factors for selenium and salt or total dissolved solids (TDS).

Selenium (Se)	Salt or Total Dissolved Solids (TDS)
1 part per billion (ppb) = 1 microgram/liter (μg/L)	1 part per million (ppm) = 1 milligram/liter (mg/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 micrograms/acre-foot at 1 μg/L	1,233,532 milligrams/acre-foot at 1 mg/L
1.23 grams/acre-foot at 1 μg/L	1,234 grams/acre-foot at 1 mg/L
454 grams = 1 pound (lb)	454 grams = 1 pound (lb)
0.00272 lbs/acre-foot at 1 μg/L	2.72 lbs/acre-foot at 1 mg/L
[1 μg/L = 0.00272 lbs/acre-foot]	[1 mg/L = 2.72 lbs/acre-foot]
	2000 lbs = 1 ton
	1 mg/L = 0.00136 tons/acre-foot
Volume	
1 cubic foot per second (ft^3/s) = 1.98 acre-feet/day	

Characteristics of agricultural subareas

Evaluation of demand for drainage and estimates of potential selenium loads requires consideration of specific agricultural subareas in the San Joaquin Valley (Northern, Grassland, Westlands, Tulare, and Kern subareas, figs. 3, 4, and appendix B). Subarea analysis presented here depends on understanding the history, agricultural activity, and geohydrologic characteristics of each designated area. A brief summary is given below for each subarea designated by the Drainage Program (1989 and 1990a). Data given in parentheses are from the Drainage Program (1989). Detailed data are given in appendix B.

Westlands Water District and Subarea
(770,000 total acres; 576,000 irrigated acres; 5,000 acres with subsurface drains, alleviating salinization in 42,000 acres)

The Westlands subarea (figs. 3 and 5) was the first to discharge irrigation drainage to the San Luis Drain (appendix B, table B1). Drainage was released into Kesterson National Wildlife Refuge from 1981 to 1986. As a result of the ecological crisis associated with Kesterson National Wildlife Refuge, the Westlands subarea now has a policy of no discharge. Drainage is recycled onto farmlands and/or stored in underlying ground-water aquifers, where irrigation and aquifer supplies are used for dilution. As a result of a recent U.S. Court of Appeals decision (Hug and others, 2000), the USBR is initiating a process to provide drainage service to the San Luis Unit (USBR, 2002a, 2005).

The data record from the Westlands subarea is particularly limited with no specific monitoring for selenium since closure of the San Luis Drain in 1986. Only data on ground-water elevations (Westlands Water District, 1998) are available in the area most affected by geologic sources of selenium. This area is potentially the greatest generator of selenium in San Joaquin Valley because it, more than any other subarea, encompasses the Panoche Creek alluvial fan (Presser and others, 1990). This fan and interfan area receive the most seleniferous runoff and erosion from the Coast Ranges (Tidball and others, 1986, 1989; Presser, 1994b).

Used here are the estimates of areas of shallow ground water that affect farming presented in management plans, testimony, and a recent status report (Westlands Water District, 1996, 1998). The Westlands Water District specifically contended (State Board, 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 Westlands Water District 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-ft of drainage per year (for example, 200,000 acres × 0.3 acre-ft per acre = 60,000 acre-ft) (USBR, 1992; Westlands Water District, 1996) (appendix B, table B2).

Because discharges from the Westlands subarea were discontinued in 1986, no current direct measurements of effluent quality are available. Historic discharges provide some guidance. In 1983 and 1984, average selenium concentrations in discharges from the San Luis Drain to Kesterson National Wildlife Refuge ranged from 330 to 430 µg/L selenium (State Board, 1985; Presser and Barnes, 1984, 1985) and as quoted from regulatory documents, from 230 to 350 µg/L (Westlands Water District, 1996) (table 3). This resulted in an annual discharge of 4,776 lbs selenium and a discharge of 17,400 lbs to Kesterson Reservoir over the history of drain usage by Westlands Water District (January 1981 to September 1985) (USBR, 1986) (appendix B, table B1). The cumulative 17,400 lbs selenium is termed here as one *kesterson* (kst). The use of this unit provides perspective on the mass of selenium that was a hazard to wildlife when released directly to a wetland (Presser and Piper, 1998).

Testimony in legal proceedings summarized data for selenium concentrations in broader areas of shallow ground water in the Westlands Water District (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 selenium 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 to 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 San Joaquin Valley is to the north and downslope of the Westlands Water District (Drainage Program, 1990a) (fig. 3). The Grassland subarea contains 70,000 to 100,000 acres of land that have historically contributed the majority of subsurface drainage to the San Joaquin River (appendix B, table B3). Adjacent Federal, State, and private riparian wetlands contain the largest tract of habitat remaining in the San Joaquin Valley. Varying lengths of the complex channel system within the wetlands convey agricultural drainage to the San Joaquin River. Mud and Salt Sloughs (figs. 3 and 4) are examples of tributaries flowing through the wetlands of the Grassland Resource Conservation District and the San Luis National Wildlife Refuge Complex that have conveyed drainage at certain times. In 1995, the discharge from about 100,000 acres of farmland was consolidated into a 28-mile segment of the original San Luis Drain (renamed the Grassland Bypass Channel) in order to reduce contaminated wetland water supplies, but discharge to the San Joaquin River via Mud Slough remains (USBR, 1995, 2001c; USBR and San Luis Delta-Mendota Water Authority, 1995 and 2001; USBR and others, 1998 and ongoing).

The available historical record from the Grassland subarea includes data from discharges to the San Joaquin River. This type of monitoring was used mainly to compare selenium concentrations in the river to water quality objectives (table 5; appendix B, tables B4 to B7; and appendix C, fig. C1). Historic data documenting selenium and salt loading to the San Joaquin River show limitations in flow and concentration measurements; and in the methodology used to calculate loads and regulatory targets (Central Valley Board, 1998f). Only recently are measurements of flow being conducted more consistently (USBR and others, 1998 and ongoing).

The effects of selenium discharges on water quality are monitored at upstream drainage source areas, at tributaries to the San Joaquin River (Mud and Salt Sloughs), and at sites on the San Joaquin River (figs. 3 and 4, Crows Landing downstream of the Merced River; and Vernalis, where the San Joaquin River enters the Delta). In general, monitoring data from 1986 to 1998 (table 5; appendix B, tables B4 to B7) showed:

1. Average selenium loads at four San Joaquin River locations were: upstream source (Grassland Area Farmers Drainage Problem Area), 8,698 lbs; Mud and Salt Sloughs combined, 7,335 lbs; Crows Landing, 8,807 lbs; and Vernalis, 9,788 lbs.
2. Annual selenium loads at the upstream source ranged from 5,083 to 11,875 lbs; at Crows Landing from 3,064 to 15,501 lbs; and at Vernalis from 3,611 to 17,238 lbs (table 5).
3. Variability in load was at least partly driven by precipitation, with larger loads discharged in wetter years than in drier years (appendix A, figs. A9 and A10).
4. Estimated selenium loads for source waters (agricultural drains or canals) differed from load estimates for the San Joaquin River monitoring sites. Some downstream estimates were higher and some were lower than the drainage source estimates. The difference among sites was usually small compared to the year-to-year variability in initial load except for unusually wet years (such as 1995 and 1998).
5. Determinations of selenium in suspended sediment, bed sediment, or biota were not performed in conjunction with water-column selenium concentrations. Reductions in downstream loads may occur because of uptake by sediment and biota (Presser and Piper, 1998). Monitoring for these types of components to determine a selenium mass balance would help to characterize the biochemical reactions that may account for the variability seen between upstream and downstream sites (Presser and Piper, 1998). Additionally, monitoring was not sufficiently frequent to accurately characterize loads during variable flows.

Analysis of available data for WYs 1997 and 1998 showed that monthly average total selenium concentrations in blended drainage ranged from 40.6 to 105.5 µg/L in (USBR and others, 1998 and ongoing) (appendix B, tables B9 and B10). The daily range was 15 to 128 µg/L over this period (appendix D, figs. D15 and D16). The annual average sele-

Table 5. Annual discharge, average selenium concentration, and selenium loads from the Grassland Drainage Source area; Mud and Salt Sloughs; and the San Joaquin River at Crows Landing and Vernalis.

[Grassland Drainage Source: problem acres 65,200 to 103,390; drained acres 47,500 to 51,000; historic drainage quality average from 1986 to 1994 was 64 µg/L. The San Joaquin River at Crows Landing is the compliance point for State regulation. The USEPA 5 µg/L water-quality criteria was exceeded at the compliance point >50 percent of the year during WYs 1987 through 1991 and during 1994. A drainage prohibition of 8,000 lbs selenium per year was enacted in 1996. NA = data not available]

Water-year	Grassland Drainage Source Areas			Mud and Salt Sloughs			San Joaquin River at Crows Landing			San Joaquin River at Vernalis		
	Volume (acre-ft)	Selenium (µg/L)	Selenium load (lbs)	Volume (acre-ft)	Selenium (µg/L)	Selenium load (lbs)	Volume (million acre-ft)	Selenium (µg/L)	Selenium load (lbs)	Volume (million acre-ft)	Selenium (µg/L)	Selenium load (lbs)
1986	67,006	52	9,524	284,316	8.6	6,643	2.67	1.6	11,305	5.22	1.0	14,601
1987	74,902	54	10,959	233,843	12.0	7,641	0.66	4.9	8,857	1.81	1.8	8,502
1988	65,327	57	10,097	230,454	13.0	8,132	0.55	6.2	9,330	1.17	2.7	8,427
1989	54,186	59	8,718	211,393	14.1	8,099	0.44	6.3	7,473	1.06	3.0	8,741
1990	41,662	65	7,393	194,656	14.6	7,719	0.40	5.6	6,125	0.92	3.0	7,472
1991	29,290	74	5,858	102,162	14.0	3,899	0.29	4.5	3,548	0.66	2.0	3,611
1992	24,533	76	5,083	85,428	12.6	2,919	0.30	3.7	3,064	0.70	1.9	3,558
1993	41,197	79	8,856	167,955	15.0	6,871	0.89	3.5	8,379	1.70	1.9	8,905
1994	38,670	80	8,468	183,546	16.0	7,980	0.56	4.8	7,270	1.22	2.3	7,760
1995	57,574	76	11,875	263,769	14.9	10,694	3.50	1.6	14,291	6.30	1.0	17,238
1996	52,978	70	10,034	267,344	13.0	9,697	1.44	3.0	10,686	3.95	1.1	11,431
1997	37,483	62.5	7,097	NA	30.0[a]	NA	4.18	2.9	8,667–9,054	6.77	0.6	11,190
1998	45,858	66.9	9,118	NA	27[a]	NA	5.13	1.6	13,445–15,501	8.5	NA	15,810
1986–1995		0.4–286[b]			0.5–59[b]			0.4–17[b]			0.4–9.6[b]	
1997–1998)		15–134[b]			3–104[b]			0.1–8.2[b]			0.1–8.2[b]	

Data sources: Drainage Problem Area, Central Valley Board, 1996b, c; 1998d through h; 2000b, c (note: In 1996, the board recompiled data from 1985 through 1995; therefore, some calculations and referenced values may be based on earlier versions of compiled data). Grassland Bypass Channel Project monthly, quarterly, and annual reports (http://www.sfei.org/grassland/reports/gbppdfs.htm; USBR and others, 1998 and ongoing).

[a] Mud Slough only.

[b] Daily range.

nium concentration observed in collected drainage from the Grassland area was 62.5 µg/L in WY 1997 and 66.9 µg/L in WY 1998 (USBR and others, 1998 and ongoing) (table 5 and appendix B, tables B9 and B10). These averages are comparable to the historical average of 67 µg/L from 1986 to 1994 and the planning estimate of 150 µg/L used by the State (Central Valley Board, 1998d, e, f, g, h) (table 3). Modeled discharges from the Grassland subarea were estimated at 80 to 120 µg/L selenium (Drainage Program, 1990a; Central Valley Board, 1996a, b) (table 3).

Tulare Subarea

(883,000 total acres; 506,000 to 551,000 irrigated acres; 42,000 drained acres)

Kern Subarea

(1,210,000 total acres; 686,000 irrigated acres; 11,000 drained acres)

The Tulare and Kern subareas are located in the southern San Joaquin Valley and discharge to privately owned evaporation ponds. Discharges to evaporation ponds are considered here in selenium load scenarios, although it is not clear whether an extension will be built to the south to include the Tulare and Kern subareas in the overall drainage solution. The inclusion of the Tulare and Kern subareas when considering the extent of the San Joaquin Valley contamination is also consistent with other comprehensive assessments.

From 1975 to 1990, 16 ponds covering 5,900 acres were developed in the Tulare subarea; ponds covered 1,300 acres in the Kern subarea (Drainage Program, 1989). Since that time, no new ponds have been built and many ponds have closed (Central Valley Board, 1997, 1998c) (appendix B, tables B19 to B21). The subareas are internally drained basins with relict lakebeds (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 the Coast Ranges and the Sierra Nevada. The geochemistry of soils and shallow ground waters is controlled by depositional zones (alluvial fan, basin trough, or lake bed) and depositional environments (oxidizing or reducing). Concentrations of selenium, uranium, arsenic, molybdenum, and boron are elevated in specific zones (Fujii and Swain, 1995). Geomorphological features affect the placement and number of subsurface drains installed in the subareas. Subsurface drains are mainly limited to lower elevations of the lakebeds (42,000 acres in Tulare subarea and 11,000 acres in Kern subarea) (Drainage Program, 1989).

Initial estimates made by the Drainage Program (1989) showed the Tulare subarea with 320,000 acres of land with ground-water levels within 5 ft of land surface. Estimates for the Kern subarea showed 64,000 acres are affected. For 2000, the estimate of affected acres increased to 366,000 in Tulare subarea and 100,000 acres in Kern subarea. Data collected by the State of acreage adversely affected by shallow ground water were considered *gross estimates* because of sparse data and extrapolation over a 696,000-acre study-area (the Tulare Lake region) (Department of Water Resources, 1997). The State study area boundaries differed from those given above as part of the Drainage Program designation.

Evaluation of selenium concentrations in Tulare and Kern subareas was limited to annual reporting by dischargers as required by the State as part of permit requirements for discharges to privately owned evaporation ponds (Central Valley Board, 1993, 1997, 1998c; State Board, 1996a; Anthony Toto, Central Valley Board, personal commun., January, 1998) (appendix B, tables B19 to B21). Selenium concentrations in discharges from the Tulare subarea to private evaporation ponds are remarkable for being low when compared to selenium concentrations in discharge from Westlands or Grassland subareas. The record is limited, but values measured in 1988, 1989, and 1993 through 1997 showed most selenium concentrations were below 10 µg/L, with the exception being the South Tulare Lake Drainage District discharge of up to 30 µg/L. Some higher selenium concentrations, ranging up to 760 µg/L, 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 discharges to evaporation ponds in 1988, 1989 and 1993 to 1997 showed selenium concentrations ranged from 83 to 671 µg/L, with the exception being the Lost Hills Ranch discharge of about 2 µg/L (Central Valley Board, 1990a, b). In general, selenium concentrations in discharges from the Tulare subarea are < 50 µg/L and for the Kern subarea are > 180 µg/L.

Northern subarea

(236,000 total acres; 157,000 irrigated acres; 26,000 drained acres)

The Northern subarea is considered here and in load scenarios for consistency with other regional evaluations. The Northern subarea presently drains to the San Joaquin River through both discharge and ground-water seepage. Estimates of acres requiring drainage have not been updated since 1990 and current records evaluating selenium are not available for compilation from this subarea. Most estimates suggest that drainage needs are relatively small compared to other areas (CH2M HILL, 1988; Drainage Program, 1990a) and will remain so if access to the San Joaquin River for drainage is available to the same degree (that is, the subarea remains in hydrologic balance).

Development of load scenarios

While most technical evaluations stop with estimates of *problem acreage* and *problem water volumes*, understanding the range of possible selenium concentrations in drainage is critical to evaluating potential loads. To bracket possible selenium concentrations in different scenarios of selenium loads from the western San Joaquin Valley, three concentrations are used in conjunction with different estimates of drainage and acreage to generate load projections (see detailed analysis in appendix B). In general, a concentration of 50 µg/L selenium 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 selenium concentration to an overall 50 µg/L; then this product water would be disposed of in an extension of the San Luis Drain. Therefore, one scenario used here is that such treatment options will be available, and/or mixtures of drainage water will resemble those presently being released from the Grassland subarea (62 to 66 µg/L selenium). For this case, a selenium concentration of 50 µg/L is used to represent treated or blended (diluted) drainage.

Other load scenarios used here will assume a maximum case of 300 µg/L selenium and an intermediate possibility of 150 µg/L selenium [an average for present day subsurface drainage waters in the Grassland subarea (Central Valley Board, 1996c); near the mean (163 µg/L) presented for the 42,000 acres in Westlands Water District (Stevens and Bensing, 1994); and a conservative estimate (at least 150 µg/L) in Westlands Water District by USBR (Wanger, 1994)]. Even though the recent public record is limited, these estimates may be conservative given the quality of the ground water and the magnitude of selenium accumulation in the internal reservoirs of the western San Joaquin Valley (table 3; appendix A). Adequate monitoring to trace ground-water movement and selenium concentrations as a function of time is needed to assess the ongoing affect of management actions aimed at more storage and less leaching (also see appendix D).

One further approach used here to project potential total selenium loads from the San Joaquin Valley is to generate scenarios using a compilation of data on selenium concentration and volume that has become available for each subarea since the Drainage Program (1985 to 1990) (appendix B, tables B9, B10 and B19 to B21). It is recognized that this involves use of data that all have significant limitations. However, the existing area-specific data incorporate the geographical heterogeneity of drainage in establishing the boundaries of potential selenium discharges. Hence, this type of approach to develop scenarios may be particularly reflective of specific geologic and hydrologic conditions in each of the five subareas.

Load scenarios based on management alternatives for all subareas

The total *out-of-valley* drainage selenium load is the sum of annual selenium loads potentially discharged from all five subareas (figs. 3 and 4) (table 6). Each scenario is specific to a Drainage Program management option (implementation, *with future*; no implementation, *without future*; and *with targeted future*) and a projected year (years 1990, 2000, and 2040) (table 6). These scenarios based on the broad Drainage Program approach, do consider, to some extent, addressing the longer-term problem of an accumulated imbalance of water, salt, and selenium and the sustainability of agriculture in the San Joaquin Valley, rather than only managing an annual imbalance.

A wide range of selenium loads from the western San Joaquin Valley is possible in the future given the ranges of acre-feet of drainage and drainage quality compiled from management options of the Drainage Program. If the volume of drainage water is assumed not to increase beyond the volume of subsurface drainage that existed in 1990 (100,000 acre-ft) and the assigned concentration of selenium is 50 µg/L, then 13,600 lbs selenium per year are projected. Assigned selenium concentrations of 150 µg/L or 300 µg/L would yield loads of 40,800 or 81,600 lbs selenium per year, respectively.

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

A scenario using an assigned concentration of 150 µg/L selenium to represent generic subsurface drainage and a Drainage Program estimate of subsurface drainage of 144,000 acre-ft (*with future*) in year 2000 yields a load of 58,752 lbs selenium per year. For year 2040 under the condition of implementation of the Drainage Program (303,600 acre-ft per year), the discharged load would be 41,290 lbs selenium per year.

Using an assigned concentration of 300 µg/L selenium in year 2000 and the least amount of estimated drainage (72,000 acre-ft per year *with targeted future*), the load discharged would be 58,573 lbs selenium per year. In year 2000, 163,000 acre-ft (*without future*) at 150 µg/L selenium would produce a load of 66,504 lbs selenium per year. In year 2040, 223,000 acre-ft (*without future*) at 150 µg/L selenium would produce a load of 90,984 lbs selenium per year.

Load scenarios based on management alternatives for individual subareas

Using the same approach as above, specific loads can be projected for each of the five subareas based on detailed data given by the Drainage Program for year 2000 (see appendix B for further analysis). Assigning concentrations of 50, 150, and 300 µg/L selenium to compiled estimates of *problem water* and subsurface drainage for each subarea generates all possibilities that result from application of different management alternatives (appendix B, table B18). A range of total loads for all subareas is also given to compare to loads projected in table 6. Appendix B (fig. B2) also illustrates use of a graphical tool to enable projection of an annual selenium load for any of the three assigned concentrations given a specific drainage volume. This type of application gives versatility and flexibility for future planning estimates.

Load scenarios based on individual subarea discharges

Loads also can be derived based on a compilation presented here of currently available data on *problem acreage*, drainage volume, and selenium concentration (appendix B, tables B9, B10 and B19 to B21). The values based on current data show only that amount discharged on the surface (such as to the San Joaquin River or to the evaporation ponds of Tulare and Kern subareas), and hence only address the present discharge being used to manage an annual imbalance of water, salt, or selenium (table 7). Depending on the type of data available from each subarea, projections are made concerning concentration or load. Because of the limited data and broad range of management alternatives across the subareas, maximum and minimum selenium concentrations are given to bracket possible load scenarios at each specific volume of drainage.

For the Northern subarea no current data is available, so a nominally assigned selenium concentration of 5 µg/L is applied as a minimum to adhere to USEPA's selenium criteria for the protection of aquatic life; a selenium concentration of 10 µg/L is applied as a maximum. The projected selenium concentration range is 68 to 152 µg/L for the Grassland subarea; 49 to 150 µg/L for the Westlands subarea (note, no

Table 6. Management alternatives and cumulative load scenarios for five subareas (Northern, Grassland, Westlands, Tulare, and Kern) using 50, 150, and 300 µg/L assigned selenium concentrations.

[Data for management alternatives, acreage, acre-feet, and acre-feet/acre/year are from Drainage Program (1990a). *Problem acres* are assumed to generate a generic *problem water* as an expression of affected acres. Tile-drained or subsurface drained acres would be expected to generate concentrated drainage as opposed to *problem water*. In the analysis here, the distinction between *problem water* and subsurface drainage helps in assigning water quality. The Drainage Program defined *without future* (no implementation of recommended plan) and *with future* (implementation of recommended plan) management alternatives. A third condition defined here as *with targeted future* applies a factor of 0.20 acre-feet/acre/year of generated drainage to estimate the lowest, although probably not realistic, irrigation water return. Also defined here is a year 2000 projection for *problem water*, which applies a factor of 0.4 acre-feet/acre/year.]

Management alternative	Problem or tile drained acreage (acres)	Generated drainage (acre-feet/acre/year)	Problem water or drainage (acre-feet)	Selenium load (lbs) at assigned selenium concentrations		
				50 µg/L	150 µg/L	300 µg/L
1990						
Without future Subsurface drainage basis	133,000	0.60–0.75	100,000	13,600	40,800	81,600
With future Subsurface drainage basis	133,000	0.40	53,200	7,235	21,706	43,411
2000						
Without future Subsurface drainage basis	269,000	Northern 0.75 Tulare 0.65–0.70 others 0.50–0.55	163,000	22,168	66,504	133,008
With future Subsurface drainage basis	360,000	0.40	144,000	19,584	58,752	117,504
With targeted future Subsurface drainage basis	360,000 (assumed from above case)	0.20 (assumed for minimum drainage)	72,000	9,793	29,376	58,753
Without future Problem water basis	444,000	0.70 (range 0.60–0.75)	314,000	42,704	128,112	256,224
0.4 acre-feet/acre/year future Problem water basis	444,000	0.40	177,600	24,154	72,460	144,922
2040						
Without future Subsurface drainage basis	386,000	Northern 0.75 all others 0.55 (minimum progress)	223,000 (243,000)[a]	30,328	90,984	181,968
With future Subsurface drainage basis	759,000	0.40 (assumed)	303,600	41,290	123,869	247,738
Without future Problem water basis	951,000	0.75 (steady increase)	666,000	90,576	271,728	543,456

[a] The Drainage Program (1990a) estimate difffers from that calculated here.

Table 7. Calculated drainage scenarios for five subareas (Northern, Grassland, Westlands, Tulare, and Kern).

[Calculations are based on evidence presented by Westlands Water District or currently available ranges of drainage volume, selenium concentration, or selenium load, except for the Northern subarea where there is no management plan recommended by the Drainage Program (tables 3, 5; appendix B, tables B9, B19–21) (Drainage Program, 1990a). Data details for subareas (also see appendices A and B): Northern: nominal 5 and 10 µg/L selenium concentrations are assigned; drainage volume is from the Drainage Program (1990, Table 3 for year 2000). Grassland: minimum is volume and load measured for WY 1997 as part of the Grassland Bypass Channel Project; maximum is an assigned selenium concentration of 150 µg/L applied to the same volume. Westlands: minimum is for condition presented as evidence for Westlands Water District; maximum condition is for the same volume of drainage, but with an assigned concentration of 150 µg/L. Tulare and Kern: volume and selenium concentration for 1993–97 (Anthony Toto, Central Valley Board, personal commun., January, 1998) from which an average volume (1993–1997) is calculated; the minimum and maximum loads are selected as the range].

Subarea or area	Drainage volume (acre-feet/year)	Selenium					Problem areas
		Minimum (lbs/year)	Minimum (µg/L)	Maximum (lbs/year)	Maximum (µg/L)	Maximum and minimum (lbs/acre-feet)	
Northern	26,000	350	5	700	10	0.014 – 0.027	–
Grassland	37,483	6,960	68	15,500	152	0.186 – 0.414	97,000
Westlands	60,000	8,000	49	24,480	150	0.133 – 0.408	200,000
Tulare	19,493	91	1.7	519	9.8	0.005 – 0.027	–
Kern	2,292	1,089	175	1,586	254	0.475 – 0.692	–
Total	145,268	16,490	–	42,785	–	–	–

current data, only testimony on acreage is available); 1.7 to 9.8 µg/L for the Tulare subarea; and 175 to 254 µg/L for the Kern subarea. Current conditions for each subarea (table 7) give ranges for annual selenium load scenarios of:

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

A graphical depiction of these projections for each subarea is given in appendix B (fig. B3). The high and low ranges of possible annual discharges are illustrated in figures 6 and 7. As noted above, the largest selenium loads come from the Westlands subarea and the Grassland subarea because of their combination of high *problem acreage*, and thus *problem water* volume, and high selenium concentration.

Choice of load scenarios (supply and demand)

Total selenium load scenarios from various combinations of subareas that might be included in a drainage collection system are summarized in table 8. These projected loads of selenium provide the basis for determining the upper and lower limits of selenium discharge from the western San Joaquin Valley that can be expected to enter the Bay-Delta either through a proposed direct conveyance to the Bay-Delta or the San Joaquin River. Secondarily, the projections provide the basis for determining the magnitude of selenium load reduction that may become necessary to achieve a specific load of selenium. Projections like those summarized (table 8) implicitly assume that selenium loads will be primarily driven by the demand for drainage, with different degrees of management superimposed. Of course, different demand scenarios than those shown also are possible.

The first four scenarios (table 8) show that the load of selenium increases from a minimum of 6,960 lbs per year to 42,785 lbs per year as additional area is added to drainage collection systems and/or as drainage volume and quality is less managed. The specific conditions for each scenario are:

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

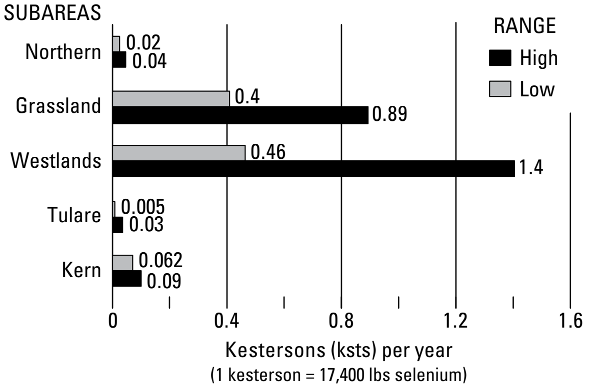

Figure 6. Projected high and low range of annual selenium discharges (in kestersons, 1 kst equals 17,400 lbs selenium as a measure of potential ecological damage based on load) from five subareas of the western San Joaquin Valley using currently available data.

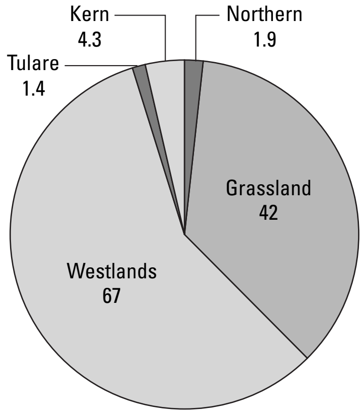

Figure 7. Projected high range of daily selenium discharges (in lbs) from five subareas shown as proportions of total discharge from the western San Joaquin Valley.

Kern and Tulare subareas, in addition to an extension to the Bay-Delta.

A future that considers only agricultural needs might call for draining all 444,000 acres of problem lands. The fifth and sixth scenarios (table 8) provide projections of selenium loads for a valley-wide drain that includes all potential problem lands estimated for the year 2000 (table 8). The first of these calculations shows the range of selenium loads expected if drainage management follows the plan submitted by the Drainage Program. If both quality (treating drainage to 50 µg/L) and quantity (such as reducing acre-feet per acre per year of drainage from 0.7 to 0.4) are managed, loads would be 19,584 lbs per year. If only quality is managed, total selenium loads for the problem lands then would 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, selenium 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-ft per acre per year, and 150 µg/L selenium drainage).

As a comparison, the final forecast (table 8) lists load *targets* given in recent TMDL or TMML management plans for discharge to the San Joaquin River from the Grassland subarea, a supply-driven strategy (USBR, 1995; Central Valley Board, 1998a) (see specifics in discussion of the San Joaquin River as a conveyance facility and appendix C). The *targeted* selenium loads range from 1,394 lbs per year to 6,547 lbs per year depending on flow (wet or dry year) (see appendix C for details; tables C1 and C2). Selenium loads measured from WY 1997 to WY 2002 under regulated Grassland Bypass Channel Project management conditions, which include storage in aquifers and surface management areas, ranged from a maximum of 9,118 lbs selenium to a minimum of 3,939 lbs selenium (USBR and others, 1995; USBR and San Luis Delta-Mendota Water Authority, 1995). Load targets for this project continue to ramp downward to 3,088 lbs in a wet year and 2,421 lbs in a dry year in WY 2009 (USBR, 1995, 2001c; USBR and San Luis Delta-Mendota Water Authority, 1995 and 2001).

Load scenarios based on the capacity of an extension of the San Luis Drain

Exports of selenium from the San Joaquin Valley also could be determined by assigning a water quality goal to the drainage in a San Luis Drain extension and operating the drain at some pre-defined capacity (table 9). The drain is presently designed to flow at 300 ft^3/s or carry about 220,000 acre-ft per year. That capacity could be a factor limiting loads, if a water quality standard is employed. Scenarios are given for (1) 50 µg/L representing an overall average given in testimony that treatment technologies or blending could achieve and near present day discharge from Grassland Bypass Channel Project to the San Joaquin River (62 to 67 µg/L); (2) 150 µg/L selenium representing an average for current subsurface drainage without blending in the Grassland subarea (Central Valley Board, 1996c) and near the mean (163 µg/L) presented for shallow ground water from 42,000 acres in the Westlands subarea (Wanger, 1994); and (3) 300 µg/L representing a concentration approaching that discharged from Westlands Water District 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 loads derived from current or potential discharges for the sum of the Grassland and Westlands subareas (table 7; 14,960 to 39,980 lbs) and that from a drain managed at full capacity at 50 µg/L (table 9; 29,920 lbs), is within the probable scenario derived from demand for drainage to manage the current annual imbalance from specific subareas (valleywide drain, all potential problem lands with management of drainage quantity and quality (19,584 to 42,704 lbs selenium, table 8). If a drainage conveyance discharges 150 µg/L selenium, at full capacity, the loading forecast (89,760 lbs selenium, table 9)

Table 8. Projections of selenium loads from the western San Joaquin Valley under different drainage scenarios.

[A kesterson (kst) is defined here as 17,400 lbs selenium, the cumulative load that caused ecological damage when released to Kesterson National Wildlife Refuge, California) (Presser and Piper, 1998)].

Scenario (subarea(s) discharging to a proposed San Luis Drain extension)	Selenium load (lbs/year)	Selenium load (kestersons/ year)	Cumulative 5-year selenium load (kestersons)
Grassland (based on current data)	6,960 – 15,500	0.4 – 0.89	2.0 – 4.45
Westlands (based on 50 – 150 µg selenium in drainage and 60,000 acre-feet)	8,000 – 24,500	0.46 – 1.41	2.3 – 7.05
Grassland and Westlands (from above)	14,960 – 40,000	0.86 – 2.30	4.3 – 11.5
Valleywide Drain (current conditions and Westlands from above)	16,490 – 42,785	0.95 – 2.46	4.75 – 12.3
Valleywide Drain (all potential problem lands with management of drainage quantity and quality)	19,584 – 42,704	1.12 – 2.45	5.6 – 12.2
Valleywide Drain (all potential problem lands with minimum management of quality and quantity)	42,704 – 128,112	2.45 – 7.36	12.2 – 36.8
Total Maximum Daily or Monthly Load Model management (load *targeted* for environment safeguards, Grassland subarea or drainage basin)	1,394 – 6,547	0.08 – 0.38	0.4 – 1.9

converges on that estimated from all problem lands with little management (42,704 to 128,112 lbs selenium, table 8).

Despite the range of assumptions and range of possible outcomes considered in tables 7, 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 selenium discharges to the Bay-Delta (1,394 to 6,547 lbs selenium). Selenium loads based on the demand for drainage converge on a mass discharge of 15,000 to 43,000 lbs of selenium per year, if volumes and concentrations are carefully managed. Loads quickly increase beyond this level if more land is drained and/or volumes or drainage quality are poorly managed or controlled (up to 128,112 lbs selenium).

Load scenarios based on the San Joaquin River as a conveyance facility (the river, in effect, as a drain)

The above projections assume drainage is conveyed in a proposed extension of the San Luis Drain and that loads are primarily defined by demand from agriculture. An alternative is to assume that water quality in the San Joaquin River would determine selenium discharges, and no drain would be constructed. Two approaches for use of the river to convey agricultural drainage have been discussed historically. Appendix C details the historical record used for derivation of loads for the San Joaquin River at Crows Landing and the load allocations for dischargers using these approaches. Both approaches consider only the amount of dilution water avail-

Table 9. Selenium loads conveyed to the Bay-Delta under different flow conditions if a constant concentration is maintained in the San Joaquin River or a San Luis Drain extension.

[Flow conditions: high flow (3.0 million acre-feet/year); low flow (1.1 million acre-feet/year); and annual flow assumed for a proposed San Luis Drain extension at maximum capacity or a small San Joaquin River input in a dry year (approximately 220,000 acre-feet/year)].

Selenium concentration in river or drain extension (µg/L)	Selenium load (lbs/year)		
	3.0 million acre-feet/ year	1.1 million acre-feet/ year	216,810 acre-feet/year (300 ft^3/s)
0.1	816	299	60
1.0	8,160	2,990	598
2.0	16,320	5,980	1,197
5.0	40,800	14,960	2,992
50	–	–	29,920
150	–	–	89,760
300	–	–	179,520

able; no consideration is given to defining the assimilative capacity of the receiving water (the San Joaquin River) based on the bioaccumulative nature of selenium. These approaches encompass both quasi-static and dynamic modeling of flows.

1. **Total Maximum Daily Load (TMDL) or Total Maximum Monthly Load (TMML) models.** This approach models load allocations based on historical flows in the San Joaquin River. A water quality standard is applied to design flows to calculate a selenium load limit for dischargers (Environmental Defense Fund, 1994). This is the technique mandated by USEPA for discharges to impaired water bodies such as the San Joaquin River (Clean Water Act, as amended, 1987; USEPA, 2000; State Board, 2002). The San Joaquin River compliance site for the 130 miles of impairment is the San Joaquin River at Crows Landing. This site is below the confluence with the Merced River, but above the San Joaquin River at Vernalis. The San Joaquin River at Vernalis, the monitoring station before the Bay-Delta, is traditionally considered the entrance to the Bay-Delta (figs. 3 and 4). Between the Merced River confluence and Vernalis, the Tuolumne and Stanislaus Rivers flow into the San Joaquin River. 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 approach goes one step further than TMDL modeling in that discharges are allocated based on real-time updates of flow (instantaneous measurements). This means maintaining a constant selenium concentration at or below a 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 selenium measurements, since technology is not available to assess selenium on a real-time basis). Loads based on real-time dilution maximize disposal of selenium 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 San Joaquin River to avoid violations of water quality objectives. This approach 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 San Joaquin River as a selenium-source water for the Bay-Delta.

The derived loads from the quasi-static TMDL and TMDL models would range from 1,394 to 6,547 lbs selenium 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 on flow regimes.

The approach presented here to develop selenium load scenarios conveyed by the San Joaquin River to the Bay-Delta considers the river as a selenium source water for the estuary using an annual static inflow for the San Joaquin River at Vernalis. The calculations also consider wet or dry year conditions and recycling. In developing this type of scenario, the starting point is the *targeted* load and the San Joaquin River is considered a drain from the San Joaquin Valley. This is a supply-driven strategy, with consideration of environmental protection a priority, rather than a strategy driven by agricultural demand. The effects on the San Joaquin River itself, of managing a constant concentrations in view of bioaccumulation, are not known and are not considered here.

In development of load scenarios, several assumptions about flow conditions were made (table 9):

- little recycling of the San Joaquin River occurs in a wet year, therefore 3.0 million acre-ft enters the Bay-Delta annually.
- 1.1 million acre-ft of San Joaquin River inflow is allowed to enter the Bay-Delta annually indicative of partial San Joaquin River inflows in a wet year or total San Joaquin River inflow in a dry year.
- nearly complete San Joaquin River recycling is 220,000 acre-ft, which is a volume comparable to the capacity of the existing San Luis Drain.

A range of 60 to 2,992 lbs selenium would actually reach the Bay-Delta under the latter flow condition (probably as in the drought years between 1987 through 1994) and selenium criteria conditions spanning 0.1 to 5 µg/L selenium (table 9). Maintaining a criterion of 5 µg/L in the San Joaquin River allows loads of 14,960 lbs and 40,800 lbs selenium per year to enter the Bay-Delta at the two higher hydraulic discharges. Maintaining a concentration at the USFWS recommended criterion of 2 µg/L at these two hydraulic conditions would result in loads of 5,980 and 16,320 lbs selenium per year.

Summary

Even though the full range of possible selenium loads 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 on management strategy:

- **Supply-driven management (3,000 to 8,000 lbs selenium per year)** By this is meant management that puts a priority on environmental protection and targets a load that cannot be exceeded. For example, the TMDL/TMML approach derives annual loads for the San Joaquin River from the Grassland subarea alone of 1,400 to 6,500 lbs to remain below a 5 µg/L selenium criterion, depending on flow regime for the San Joaquin River. The present prohibition for discharge from the Grassland subarea or drainage basin is a load of 8,000 lbs.
- **Demand-driven load with management of land and/or drainage quality (15,000 to 45,000 lbs selenium per year)** By this is meant selenium loads are driven

by agricultural demands for draining saline or waterlogged soils. The quality and quantity of the drainage are assumed 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 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 selenium (controlled concentration), yields a selenium load range of 19,584 to 42,704 lbs selenium 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 selenium 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 Drainage Program for year 2000 without implementation of the management plan (demand driven volume) in conjunction with a concentration of 150 µg/L selenium (non-controlled concentration), yields a selenium load range of 42,704 to 128,112 lbs selenium 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 selenium per year or even more.

Table 10. Ranges of annual and daily selenium loads from oil refineries located in the North Bay for the period 1986 to 1992 and 1999.

[Cleanup of discharges and further permitting was required by 1998.]

Oil refinery	Selenium load (lbs)			
	1986–92[a]		1999[b]	
	Annual	Daily	Annual	Daily
Equilon Enterprises LLC at Martinez (formerlyShell Oil)	1,203–2,595	3.3–7.1	440	1.20
Tosco Corporation at Avon	180–482	0.49–1.3	118	0.32
Tosco Corporation at Rodeo (formerly Unocal)	1,045–1,938	2.9–5.3	98	0.27
Valero Refining Company (formerly Exxon Corporation)	321–755	0.88–2.1	132	0.36
Chevron Corporation	354–1,687	0.97–4.6	327	0.90
Total	3,103–7,457	8.5–20.4	1,115	3.05

[a] Data sources: San Francisco Bay Board (1992b and 1993).

[b] Johnson Lam, San Francisco Bay Board, personal commun., September, 19, 2000.

Selenium from Oil Refineries

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

As a result of regulations imposed by the State, refinery discharges to the Bay-Delta declined after July 1998. The annual selenium load ranges reported by the State from 1986 to 1992 for the five major refineries are listed in table 10, along with loads measured in 1999 (San Francisco Bay Board, 1993). Using these estimates, refinery inputs declined by about two-thirds (to about 1,100 lbs selenium per year), from the amount measured from 1986 to 1992. On the other hand, refinery effluents also are regulated to a concentration of 50 µg/L selenium and to the volumes discharged in the late 1980s. If the volume of effluent (5,000 acre-ft) remains what it was in the late 1980s, the resulting selenium load would be 1,400 lbs selenium per year. Monitoring programs have not yet been implemented that are capable of reliably evaluating whether 1,400 lbs or 1,100 lbs selenium per year best describes refinery discharges, but the difference is relatively small considering the variability within years and within refineries (table 10).

Historic selenium discharges were > 50 percent selenite (Cutter and San Diego-McGlone, 1990). Recently instituted treatment technologies in the refineries have changed the proportions of selenium species. Recent data suggest the selenite concentration peak near the refineries has declined after the treatment technologies were implemented and selenate concentrations have increased (Cutter and Cutter, 2004).

Selenium from the Sacramento River

Most of the river inflow to the Bay-Delta comes from the Sacramento River (fig. 4). The San Joaquin River (at Vernalis) inflow is usually about 10 to 15 percent of the inflow of the Sacramento River (at Freeport). Dissolved selenium concentrations in the Sacramento River at Freeport are consistently and comparatively low, averaging 0.06 ± 0.02 µg/L (Cutter and San Diego-McGlone, 1990). Thus, the Sacramento River represents a comparatively low concentration/high volume source of selenium. Using a concentration of 0.04 µg/L selenium (a conservative estimate) and the inflows given below, the projected annual selenium loads conveyed by the Sacramento River to the Bay-Delta are:

- 32 million acre-ft, wet year: 3,482 lbs selenium per year
- 17 million acre-ft, median year: 1,850 lbs selenium per year
- 10 million acre-ft, dry to critically dry year: 1,088 lbs selenium per year
- 5 million acre-ft, most critically dry year: 544 lbs selenium per year

Selenium loads increase with volume of inflow from the Sacramento River, because selenium concentrations in the river are relatively low, but constant. Therefore, the Sacramento River inflow establishes a baseline flow and selenium concentration entering the estuary.

Summary

In the Bay-Delta selenium model (fig. 2), four sources of selenium in different proportions determine selenium loads to the Bay-Delta. Sacramento River loads vary purely as function of inflow volumes (1,850 lbs selenium per year, median precipitation year). Potential loads from an extension of the San Luis Drain vary widely. Projected supply-driven loads are lowest; demand-driven loads with management and treatment capabilities fall within the range of 15,000 to 45,000 lbs selenium per year. Loading rates escalate steeply if treatment strategies are not applied. Projected loads from the Grassland subarea or drainage basin, as regulated concentrations in the San Joaquin River, vary from approximately 1,400 to 6,547 lbs selenium per year. However, the load from the San Joaquin River entering the Bay-Delta is ultimately constrained by the quantity of river water that reaches the estuary. Oil refinery loads are assumed to remain at post-1998 values reflecting regulation and treatment technology (about 1,400 to 1,100 per year). The sums of combinations of these loads represent different management and hydraulic condition scenarios. A few specific, and most likely, scenarios for the Bay-Delta are considered in detail for forecasting selenium concentrations in water, sediment, and food webs; and for subsequent evaluation of ecological effects on predators (birds and fish) in the Bay-Delta.

Hydraulic Connections and Conveyance of Selenium to the Bay-Delta

Selenium loads from the San Joaquin Valley can be conveyed to the Bay-Delta either through the San Joaquin River or a proposed extension of the San Luis Drain. As discussed earlier, the originally planned valleywide drain or San Luis Drain was a proposed canal that would collect irrigation drainage valleywide or from the San Luis Unit (Westlands subarea and parts of what is now the Grassland subarea) and transport it directly into Suisun Bay at Chipps Island (see also table 1; figs. 3 and 4; and appendix A). If extensions of the San Luis Drain are constructed, the drain could potentially collect drainage from all five subareas of the western San Joaquin Valley; or, as currently proposed and configured, from Westlands subarea and Grasslands subarea only and release it directly into the Bay-Delta (figs. 3 and 4).

The San Joaquin River is the only natural outlet from the San Joaquin Valley. A substantial proportion of the freshwater flowing toward the Bay-Delta from its watershed is diverted (exported) for agricultural and urban uses. Before the 1990s, the San Joaquin River was almost completely diverted and recycled back south (fig. 4). That meant little or none of the selenium discharged into the San Joaquin River as agricultural drainage reached the Bay-Delta. After the 1994 Bay-Delta Water Accord (State Board, 1994), water management changed; more selenium will reach the Bay-Delta as less recycling of the San Joaquin River occurs. However, not all water that remains in the San Joaquin River at Vernalis enters the Delta or the Bay. The merging of the Sacramento River and San Joaquin River systems in the estuary and exports or water diversions (figs. 8 and 9) add complexity to likely scenarios. The amount of potentially selenium-laden San Joaquin River inflow reaching specific locations in the Bay-Delta is influenced by (State Board, 1999a; Monsen, 2000):

- tidal cycles;
- variable inflows of the Sacramento River and San Joaquin River due to seasonality and upstream withdrawals;
- quantity of water diverted (pumped) from the Delta to the Central Valley Project, State Water Project, and local water users through the California Aqueduct, Delta Mendota Canal, and Contra Costa Canal;
- discharge of agricultural drainage from the San Joaquin Valley and 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, 1999a, b, c, d).

Figures 8 and 9 show the balance of water for the Bay-Delta in a wet year (1996) and in a dry year (1994) among:

- total river (Sacramento River and San Joaquin River) inflow;
- San Joaquin River inflow;
- water diversions [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 San Joaquin River discharges are exceptionally 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, San Joaquin River inflow at Vernalis can be a large proportion of total inflows. During this time of year, if San Joaquin River 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 San Joaquin River inflow reaches the Bay-Delta during this time of year. Better understanding of water movement from the San Joaquin River through the Bay-Delta and processes within the estuary are critical to future evaluations of selenium issues. Evaluations of the implications of water management decisions need to consider effects on selenium transport and residence time. A large range of residence times have been estimated for freshwater in various parts of the Bay-Delta (Walters and others, 1985). The estimated residence times for high flow and low flow periods are:

- Suisun Bay: high flow, 0.5 day; low flow, 35 days
- San Pablo Bay: high flow, 0.8 day; low flow, 25 days

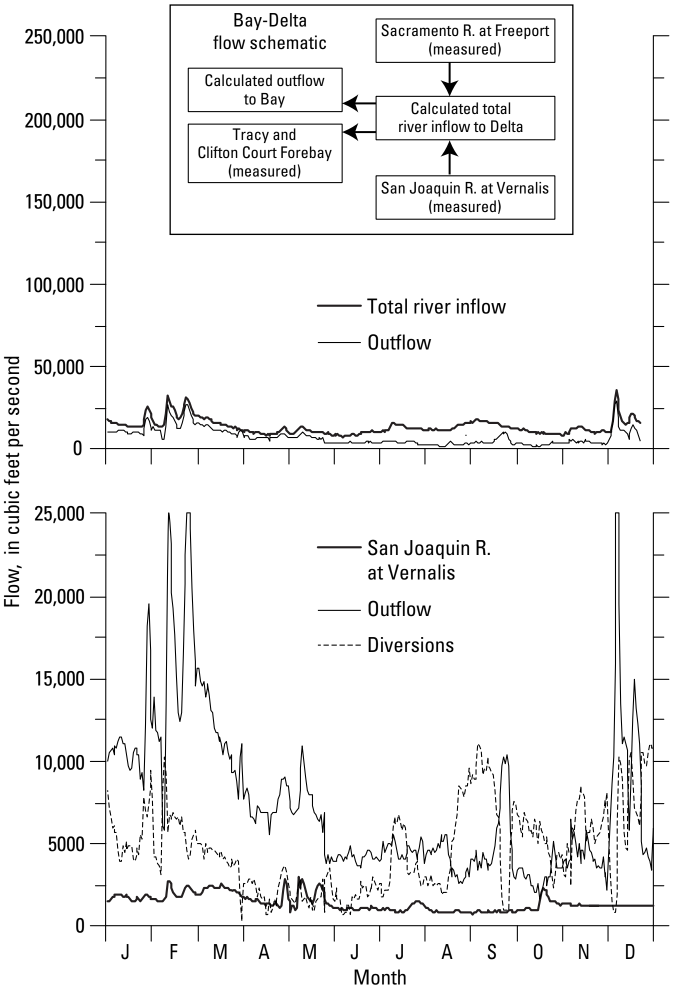

Figure 8. For a dry year (1994), the balance among flow of the San Joaquin River at Vernalis, total river inflow (San Joaquin at Vernalis and Sacramento River at Freeport combined), water diversions (pumping at Tracy and Clifton Court Forebay), and outflow to the Bay.

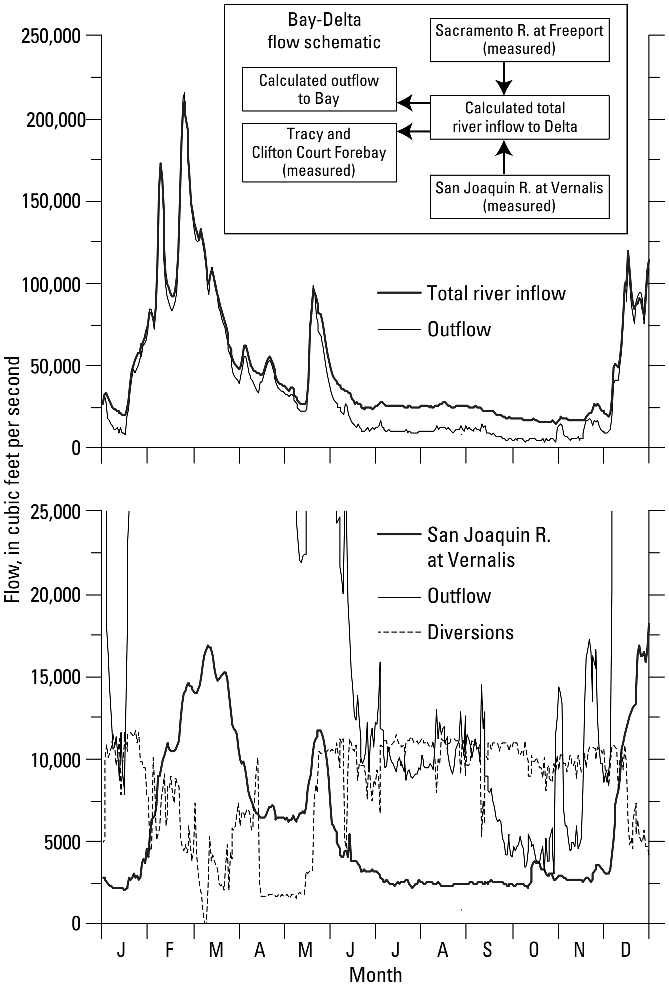

Figure 9. For a wet year (1996), the balance among flow of the San Joaquin River at Vernalis, total river inflow (San Joaquin at Vernalis and Sacramento River at Freeport combined), water diversions (pumping at Tracy and Clifton Court Forebay), and outflow to the Bay.

- Northern reach: high flow, 1.2 days; low flow, 60 days
- South Bay: high flow, 120 days; low flow, 160 days
- South Bay (north of Dumbarton Bridge): high flow, 80 days; low flow, 120 days
- Extreme South Bay (south of Dumbarton Bridge): high flow, 40 days; low flow, 70 days

Concentrations of Selenium in the Bay-Delta

Effects of Source Water Selenium Loads on Receiving Water Selenium Concentrations

Interpretation of mass loads from individual sources requires understanding how load and volume in different source waters combine to produce concentrations in receiving waters. For the modeling approach used here, determining selenium concentrations in Bay-Delta receiving waters is the initial step in a series of linked steps that determines biological effects from selenium (fig. 2). So ultimately the interaction between source water load and receiving water concentration must be understood.

In general, selenium loads in agricultural source waters from the western San Joaquin Valley may increase with increased applied water, given the characteristics of selenium concentrations in subsurface drainage and the massive storage of selenium in aquifers (fig. 5; appendices A and B). Loads also increase with the volume of inflow from the Sacramento River, because selenium concentrations in the river are relatively constant. On the other hand, concentrations in a mixture of waters where sources combine will be dependent on the sum of the volumes of the sources and the masses of selenium in each of those sources. Dissolved selenium constitutes 80 to 93 percent of the total selenium (Cutter, 1989) in the Bay-Delta, so loads based on total selenium can be used to derive concentrations of dissolved selenium.

The volume of water flowing into 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 San Joaquin River. Monitoring of selenium concentrations in 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 about June, followed by lower inflows through the last six months of the calendar year (Conomos, 1979; Conomos and others, 1985).

In contrast to selenium loads dependent on water volumes, the mass of selenium from anthropogenic sources such as oil refineries is not highly variable because both effluent volumes and concentrations are relatively constant (State Board, 1992a, b). Permits include restrictions on both concentrations and loads to achieve environmental targets.

Discharge from a San Luis Drain extension also could act as a traditional effluent that is regulated through volume, concentration, or load. Historically, the Westlands subarea during 1981 to 1985, discharged an average concentration of 330 to 430 µg/L selenium, with an average volume of about 570 acre-ft per month (appendix B, table B1). Monthly load targets for regulated discharge to the San Joaquin River in WY 1997 varied from 348 to 1,066 lbs selenium, with the largest loads discharged during February (appendix B, table B9). Average volumes of agricultural drainage during that time varied from 1,274 to 4,867 acre-ft per month, with average monthly concentrations varying from 25 to 106 µg/L selenium to enable regulation. In all these cases, the degree of variability in volume of sources is small compared to the variability in river inflows.

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

- [composite source load] = sum of loads from each source (six-month season or monthly)
- [composite source volume] = sum of volumes for each source (mainly inflows of Sacramento and San Joaquin Rivers) (six-month season or monthly)
- [composite source concentration] = [composite source load] ÷ [composite source volume]

Specifically for Bay-Delta modeling, a *composite freshwater endmember selenium concentration* is calculated for a hypothetical location in the North Bay at the head of the estuary where all sources combine (all loads contribute to a freshwater endmember near the site of input) with instantaneous mixing. A selenium concentration also is calculated for Carquinez Strait, a point midway in the North Bay (at a salinity of 17.5 psu, practical salinity units).

In wet years (high precipitation), reduced selenium concentrations are expected in Bay-Delta receiving waters; in dry years and dry seasons, concentrations in receiving waters will increase. Therefore, evaluations of selenium effects must consider the time periods before, after, and during low flow periods, because this is when the highest concentrations of selenium will occur. Dry years and dry seasons will be times that govern ecological effects (that is, will be ecological bottlenecks) with regard to selenium. Factors such as residence times and exchanges within the Bay and Delta are also important, but models necessary to understand these smaller scale effects (such as elevated concentrations near sources of inflow;

detailed distribution within the Delta or Suisun Bay) are not adequately developed. Further development of hydrodynamic models (Cheng and others, 1993; Monsen, 2000; Monsen and others, 2002) multiple media mass balance models, and kinetic geochemical models are important to defining detailed ecological effects of selenium and to resolving future selenium problems.

Existing Concentrations in the Bay-Delta

Regional baseline

Dissolved selenium concentrations are 0.06 ± 0.02 µg/L in the Sacramento River (at Freeport) (Cutter and San Diego-McGlone, 1990) and 0.02 to 0.08 µg/L in the seawater with which it mixes in all seasons (Cutter and Bruland, 1984). The regional selenium baseline for the Bay-Delta used here is defined by mixing selenium concentrations in these two endmembers, as determined by a salinity gradient through the estuary (fig. 10). A more complex case is one of a composite freshwater endmember comprised of the Sacramento River, the San Joaquin River, and refinery effluents. The regional baseline can be compared to a theoretical mixing line for which a selenium endmember concentration in a freshwater composite represents anthropogenic sources. In figure 10, the example mixing profile gives a selenium concentration of 0.23 µg/L. This composite freshwater endmember concentration is calculated from annual selenium loads and volumes in the Sacramento River at 20 million acre-ft (typical conditions in a wet year before refinery cleanup) plus a refinery load of 4,400 lbs selenium per year (table 10). The gradient thus shows selenium concentrations through the estuary as an 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 selenium concentrations in the Bay-Delta. This approach to modeling selenium discharges to the Bay-Delta illustrates that variation in selenium loads delivered by an endmember consisting only of the Sacramento River will not cause changes in average selenium concentrations in the Bay-Delta. This is because average selenium concentrations in the river are relatively constant (within the range of 0.04 to 0.08 µg/L). However, the sum of source selenium loads determines the selenium concentration of a composite freshwater endmember. Hence, adding a low volume/high concentration source of selenium to obtain a composite freshwater endmember selenium concentration will cause changes in the selenium concentrations in the estuary system.

The spatial details of observed selenium distributions can be compared to theoretical distributions in order to draw conclusions about internal sources or trapping of selenium within the estuary. The projected selenium concentration in the theoretical composite freshwater endmember used above (0.23 µg/L) is similar to the selenium concentration observed in surveys of the estuary (see discussion below and Cutter and Cutter, 2004).

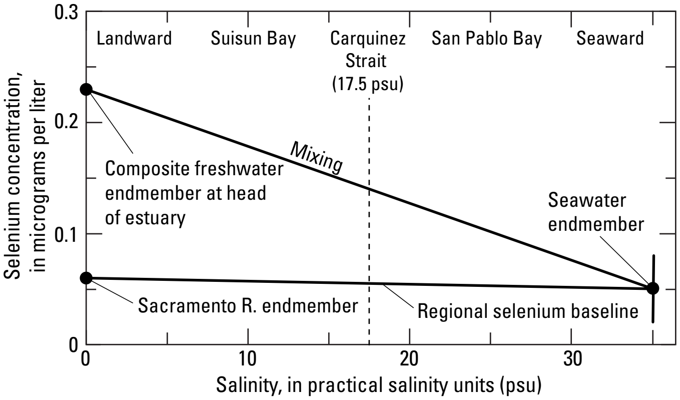

Figure 10. Hypothetical dilution profiles for selenium in the Bay-Delta: (1) the regional baseline profile shows selenium concentrations through the estuary as concentrations in the Sacramento River are diluted by concentrations in the Pacific Ocean as indicated by salinities; (2) the example mixing profile shows the selenium concentration in a hypothetical average freshwater endmember as it is diluted by concentrations in the Pacific Ocean.

Concentrations observed in the Bay-Delta

Five studies have been conducted that employed a reliable methodology for the analysis of dissolved selenium 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 and Cutter (2004) (also see data quoted in Luoma and Fisher, 1997) sampled the salinity gradient again in May 1995 and October 1996. Since its inception in 1993, the San Francisco Estuary Regional Monitoring Program also has analyzed selenium 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 selenium concentrations less than the 1 µg/L criterion designated by Canada (Environment Canada/Health Canada, 1995; Outridge and others, 1999); the 2 µg/L USFWS recommended 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/L USEPA chronic criterion for protection of aquatic life (derived from freshwater studies) (USEPA, 1992). The maximum concentrations of dissolved selenium in most surveys are less than those observed in the adjacent watersheds (Cutter, 1989; Cutter and San Diego-McGlone, 1990; San Francisco Bay Board, 1992a , b, 1993) (tables 3 and 5). Slightly higher concentrations are sometimes observed near the Golden Gate Bridge, but these appear to originate from the South Bay (Cutter, 1989). The highest dissolved selenium concentration observed in any North Bay survey was 0.44 µg/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/L). Few surveys have been conducted of selenium concentrations in the Delta, although a recent CALFED supported study has begun some data collection in this area (see for example, Lucas and Stewart, 2005).

The spatial features of the selenium gradient in the North Bay (fig. 11) were initially described by Cutter (1989). Surveys done between 1986 and 1996 show that selenium concentrations are (1) highest in Suisun Bay, in the mid-salinity ranges near Carquinez Strait; and (2) lowest in river and oceanic endmembers. This suggests a source of selenium exists in the middle of the estuary. Cutter (1989) determined that oil refineries were that source, an observation consistent with the distribution of biologically available selenium reported by Johns and others (1988).

Seasonal and year-to-year variations in river inflows influence dissolved selenium concentrations in the Bay-Delta. Higher concentrations appear to occur during periods of low inflow than during periods of high inflows (fig. 11). Spatial distribution also changes with inflows from the rivers. In April 1986, after a large flood in February, dissolved selenium declined linearly from freshwater to seawater, correlating with salinity. Estimates of fluxes indicate that the export of selenium from the Bay-Delta to the ocean was controlled by riverine sources during this month. During low flow seasons, dissolved selenium concentrations increase and a peak in Suisun Bay becomes more distinct. Cutter (1989) and Cutter and San Diego-McGlone (1990) showed that in September 1986, total input from the rivers was 2.45 lbs selenium per day (or extrapolated, 894 lbs per year) and from internal sources was 17.9 lbs selenium per day (or extrapolated, 6,534 lbs per year). Flux calculations from different sources indicated that the selenium load from refineries was 2- to 8-times that from the rivers in this month, and was the cause of the shape of the gradient. In March of 1987, during a drought, refineries accounted for 74 percent of the selenium flux; in May 1987 they accounted for 96 percent. Recent data suggest that selenium fluxes have changed since regulatory limits took effect in July 1998, but the relative proportion of source waters remain approximately the same (Cutter and Cutter, 2004)._

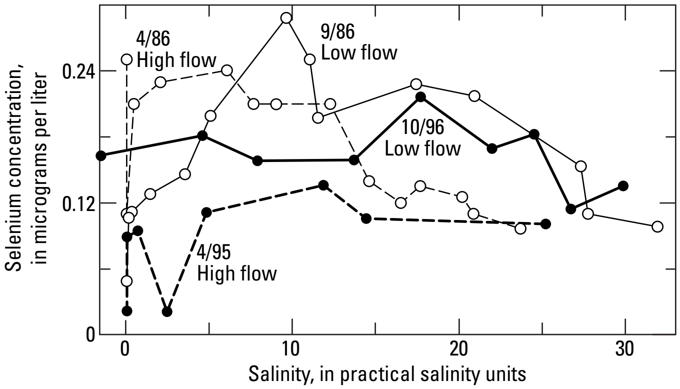

Figure 11. Dissolved selenium concentration profiles as function of salinity in the Bay-Delta during high and low flow seasons in 1986 and in 1995 – 96.

Thus, while estuarine waters in the Bay-Delta are enriched in selenium compared to the regional baseline, selenium concentrations in estuarine waters are low compared to many contaminated freshwater environments. The concentration of dissolved selenium 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 µto 0.39 µg/L. Presumably some of these sites also are anthropogenically contaminated. This range of dissolved selenium 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 selenium concentrations result in the degree of food web contamination described next.

Chemical Forms of Selenium (Speciation)

Concentrations of waterborne selenium are not sufficient to predict the biological implications of selenium contamination. The geochemical speciation of selenium is a critical consideration. Speciation of dissolved selenium ultimately controls transformation reactions between dissolved and particulate forms (such as sediments, detrital particles, and primary producers). Transformations and particulate concentrations are important factors determining the biological effects of selenium; 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

Equilibrium thermodynamic calculations do not accurately predict the speciation of selenium in oxidized natural waters because of the influences of biological processes (Luoma and others, 1992). In such waters, selenium exists in a variety of oxidation states. Biological accumulation by microorganisms, reductive bioproduction of organoselenium and, release of the latter contribute to the disequilibrium. Dissolved selenium in aerobic waters can sometimes occur predominantly as organo-Se and this species may be important seasonally (Takayanagi and Wong, 1984; Cutter and Bruland, 1984; Presser and others, 2004b). However, selenate and selenite usually are the common dissolved forms.

In nature, bioaccumulation of selenium into food webs can be more proficient and biotic consequences to birds and fish more severe when a source water is selenite-dominated, than when it is selenate dominated (Skorupa, 1998a). However, generalizations about effects based on comparative toxicity and bioavailability of different selenium species in water (for example, Maier and others, 1993) must be used with caution. As illustrated in the approach used here, overall conclusions about bioavailability are dependent on linking receptors to foodweb components using very detailed species-specific analysis.

Examples exist in nature where each of the three major species of selenium 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; Skorupa, 1998a); and (3) organo-Se can predominate where selenium is strongly recycled (Takayanagi and Wong, 1984). In the Bay-Delta, speciation differed among the source waters in 1980s (Cutter and Diego-McGlone, 1990):

- Sacramento River inflow was 30 to 70 percent selenate, depending on season; organo-Se was the other main component.
- San Joaquin River inflow was 70 percent selenate and 22 percent organo-Se.
- refinery wastewaters averaged 62 percent selenite.
- in the late 1980s, during low flow in Carquinez Strait, as much as 50 percent of the selenium was selenite, reflecting the predominance of refinery inputs.
- in the late 1990s, preliminary studies in Suisun Bay showed less selenite, but selenite plus organo-Se could constitute 60 percent of the mass of selenium.

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 selenium is the partitioning reactions that determine the distribution between dissolved and particulate phases, where particulate phases include primary producers (such as phytoplankton), bacteria, detritus, suspended inorganic material, and sediments. There are several reasons these reactions are important:

- The pathway for nearly all selenium transfer to the second trophic level in an ecosystem is through particulate forms (animals bioaccumulate selenium from their food to a much greater extent than they take up selenium from water, at the distributions typical of nature (Luoma and others, 1992; Luoma and Rainbow, 2005).
- The transformation efficiency from dissolved to particulate selenium ultimately determines foodweb concentrations of the element (higher particulate material selenium concentrations means greater contamination in the food web, although the form of the selenium in the particulate also can be important);
- Particulate selenium concentrations can differ by as much as 100-fold at the same dissolved concentration depending on biogeochemical transformation reactions governing dissolved particulate interactions. Thus, forecasts of effects depend on understanding what transformations will occur.

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

The concentration per unit mass in the particulate material is more critical than the mass in suspension (per unit volume of water). In fact, the most important measure of selenium in any environment may be the concentration of selenium per unit mass of suspended particulate material. This concentration determines the exposure of the many species that feed on such material. Exposure for each species to selenium 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 concentration of selenium in food or particulate material (µg/g), along with the efficiency with which that concentration is assimilated (Luoma and others, 1992). Assimilation efficiency (AE) is the proportion of ingested selenium that is taken up into tissues (for example, into the tissues of prey organism such as bivalves); and AE varies with the type of food or the form of particulate selenium that is ingested.

Direct determination of selenium concentrations per unit mass on suspended sediments is rare. This is at least partly a result of the difficulty in collecting a sufficient mass of suspended material for direct analysis.

Transformation

Several different primary reactions can transform (or affect transformation of) dissolved species of selenium to particulate selenium. Transformation reactions include biological, redox (reduction/oxidation), 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) through uptake by plants or, perhaps microorganisms. Microbes, plants, and microflora (phytoplankton) reduce the selenium they concentrate to Se(-II). Most biochemically transformed selenium is found within the cell solution, at least in phytoplankton (Reinfelder and Fisher, 1991), and it 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 selenium in water contacts reduced particles 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 and others, 1989). Dissimilatory reduction of either Se(IV) or Se(VI) predominantly generates elemental selenium [Se(0)] in sediments; but it may also generate some operationally defined organo-Se [Schlekat and others, 2000]. Elemental selenium 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.** Particulate selenium generated by transformation reactions can occur in different oxidation states depending on the transformation reaction and subsequent exposure to geochemical conditions. Understanding the form of particulate selenium is critical to evaluating effects of selenium contamination, because each form has a different biological availability (Luoma and others, 1992). Reduction/oxidation status, determined by the balance of redox couples, is especially important in determining particulate form. Possible particulate forms include: adsorbed/coprecipitated (SeIV) and (SeVI), organic selenides [either in the form of intracellular Se(-II) or detrital Se(-II)], or elemental selenium [(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 and others, 1997, 1998; Myneni and others, 1997).

- **Volatilization**. Biogeochemical volatilization of selenium has been documented in wetland soils (Cooke and Bruland, 1987; Thompson-Eagle and Frankenburger, 1992) and in evaporation ponds (Fan and Higashi, 1998). Volatilization rates depend on physical/chemical conditions, vegetation, water management, or other rate limiting factors (Flury and others, 1997; Zhang and Moore, 1997a, c; Hansen and others, 1998). The influence of volatilization on selenium concentrations in sediments (the relevance to this discussion) is determined by the mass of selenium volatilized, compared to that in sediments. A careful mass balance including determination of selenium inputs, outputs, and internal inventories is the only way to verify effects of volatilization on selenium inventories Presser and Piper, 1998). 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 about 30 percent of the incoming selenium was volatilized at Kesterson Reservoir. Zhang and Moore (1997d) and Hansen and others (1998) reported results consistent with that figure for other wetland systems. If 30 percent is typical, it is possible to calculate the effect of volatilization on selenium concentrations in a wetland that receives a continuous influx of selenium. If 90 percent of incoming dissolved selenium is trapped in the sediments, and if 30 percent of that is volatilized, then the net effect of volatilization is to reduce the progressive accumulation of selenium in particulate material to: 0.90 trapped × 0.30 volatilized = 0.63 trapped × 100 = 63 percent of incoming selenium retained. Thus, volatilization could slow selenium accumulation to a rate less than would otherwise be achieved. However, in no known case has volatilization eliminated selenium contamination or alleviated water quality problems. Wetland trapping can remove selenium from contaminated waters, but most of the selenium remains in the sediments; efforts to completely volatilize selenium to the atmosphere have not proven successful. If selenium 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 selenium load (see, for example, Flury and others, 1997).

Range of distribution coefficients (K_d's)

The distribution coefficient (K_d) is a way to quantitatively describe the partitioning of total selenium between dissolved and particulate states. The K_d is the ratio of selenium per unit mass particulate material to selenium per unit volume water, in equivalent units. An example of a calculated K_d 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 × 103 L/kg.

Speciation of dissolved selenium and transformation reactions have a combined influence on the distribution coefficient of selenium. The K_d oversimplifies both with the result that K_d's based on total concentrations in natural waters vary by as much as two orders of magnitude. Nevertheless, the K_d is a first order measure of partitioning and the measure uses the types of data most widely available from a variety of systems. Table 11 lists K_d's typical of a variety of ecosystems from which reliable geochemical data are available. The K_d's in various field studies range from 0.2×10^3 to 4×10^4, reflecting the complicated transformation reactions and processes described above. Laboratory studies (Reinfelder and Fisher, 1991) show a range of 4.0×10^3 to 1.1×10^5, with the maximum extending somewhat above 4×10^4. Skorupa (1998a) also summarized the range of dissolved and sediment data found in various field studies. Median K_d's from that list, although not calculated by Skorupa (1998a), show a similar range. Knowing the range of K_d's in nature allows understanding of the potential range of particulate selenium 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

General sources of particulate selenium in the Bay-Delta include:

- **Autochthonous (internal) sources in the San Joaquin River or the Delta** Selenium could be transformed to particulate forms in the marshes of the San Joaquin River and the wetlands/lakes of the Delta by either dissimilatory reduction to Se(0) or biotransformation to Se(-II). Little is yet known about selenium trapping or transformation within the Delta itself.

- **Allochthonous (external) sources** It is possible that selenium contaminated particles produced in the San Joaquin River could be transported to and trapped in the Delta. Particulate selenium 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 drainage water to the Bay-Delta will transport externally and internally produced particulate selenium.

- **Autochthonous (internal) 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 selenium in the sediments of wetlands or shallow-waters (Zhang and Moore, 1997a, b). Thus, the times 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 selenium are wetlands and shallows with long residence times. Restoration activities could affect selenium contamination in the San Joaquin River/Bay-Delta system if hydraulic residence times change or a larger area of the kind of systems that trap selenium are generated, without remediating selenium inflows.

Particulate selenium in the San Joaquin River

Discharge of agricultural drainage to the San Joaquin River through canals and wetlands has long occurred. Since 1996, a 28-mile portion of the existing San Luis Drain also has discharged drainage from districts of the Grassland subarea to the river. Difficulties arise in drawing generalizations about temporal trends or spatial distributions of particulate selenium in the San Joaquin River, 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; amounts of suspended material; selenium concentrations in suspended material in different seasons; or bed sediment characteristics such as particle size and differences in organic carbon concentrations. A detailed, systematic and carefully designed study of particulate selenium occurrence and trends is a critical need. Data from 1987 through 1997 (appendix E, tables E1 and E2) show the following:

- **Upstream of San Luis Drain** Concentrations of selenium were 0.01 to <0.18 µg/g dry weight in sediments from upstream of the San Luis Drain discharge at the San Joaquin River at Lander Avenue in 1987–89. These are probably baseline concentrations of selenium for the system. In 1993–96 and 1997, concentrations upstream of the San Luis Drain discharge at Mud Slough, were within the range 0.10 to 0.44 µg/g dry weight; these higher values probably reflect contamination from historic selenium discharges when the slough transported drainage.

- **Downstream of San Luis Drain, before 1996 discharges** The range of selenium concentrations, among several studies, in sediments of the San Joaquin River downstream of the inactive discharge site (pre-1996) was 0.3 to 1.9 µg/g dry weight. One value of 5.2 µg/g dry weight was reported from the San Joaquin River near Vernalis.

- **Downstream after current operations began** In September 1996, after operation of the San Luis Drain

Table 11. Partitioning (K_d) between dissolved selenium and particulate or sediment selenium in ecosystems for which reliable analytical data is available.

[Two experimental values from Reinfelder and Fisher (1991) also are included.]

Ecosystem or organism	Selenium			Reference
	Dissolved (µg/L)	Particulate (µg/g)	Distribution coefficient (K_d)	
Kesterson Reservoir				
Pond 2	330	55–165	$0.2–0.5 \times 10^3$	Presser and Piper, 1998
Terminal pond	14	13–24	$0.9–1.7 \times 10^3$	Presser and Barnes, 1998
Belews Lake	~11	~15	1.3×10^3	Lemly, 1985
Benton Lake				
Pool 1 channel	4	10	2.5×10^3	Zhang and Moore, 1996
Pool 2	10.4	3.5	0.34×10^3	Zhang and Moore, 1996
Pool 5	0.74	0.35	0.5×10^3	Zhang and Moore, 1996
Constructed wetland	5.0–9.8	2.1–6.7	$0.2–1.2 \times 10^3$	Hansen and others, 1998
San Luis Drain	330	84	0.25×10^3	Presser and Piper, 1998
Grassland Bypass Channel Project	62.5	30	0.5×10^3	Appendix E
Delaware River (tidal freshwater)	0.17–0.35	0.6–1.5	4×10^3	Riedel and Sanders,1998
Diatoms	–	–	1.1×10^5	Reinfelder and Fisher, 1991
Dinoflagellate	–	–	4×10^3	Reinfelder and Fisher, 1991
Great Marsh, Delaware	0.01–0.06	0.3–0.7	$3 \times 10^3 – 1 \times 10^4$	Velinsky and Cutter, 1991
Bay-Delta (suspended particulate matter 1986, 1995, 1996)	0.1–0.4	1–8	$1–4 \times 10^4$	Cutter and Cutter, 2004; Doblin and others, 2006
Bay-Delta sediment	0.1–0.3	0.2–0.5	$1–5 \times 10^3$	Johns and others, 1988

began, selenium concentrations of 0.1 to 0.76 µg/g dry weight 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/g dry weight. Recent data (2002 to 2003) show selenium increasing to 8.5 µg/g dry weight in sediments in a seasonal backwater tributary of Mud Slough where residence time increases (USBR and others, 1998 and ongoing).

- **Suspended sediments** Several surveys also have analyzed suspended sediments in the San Joaquin River or adjacent marshes or sloughs. In all cases, concentrations in suspended sediments exceeded concentrations in bed sediments. The range of concentrations in suspended sediments was 0.91 to 6.7 µg/g dry weight. Systematic studies of suspended sediment in relation to seasonality, hydrology, or forms of selenium could be instructive with regard to sources and the causes of variability.

Particulate selenium in the Delta

Little is known about selenium concentrations in the Delta, but studies of specific areas of the Delta recently have been completed (see for example, Lucas and Stewart, 2005). In 1986–88, Johns and others (1988) sampled bivalves and sediments (fine-grained oxidized surface sediments, <100 µm) monthly at a station in the Old River channel near Clifton Court Forebay. At that time and location, selenium concentrations in both indicators (*Corbicula* sp., mean 3.1 µg/g dry weight and particulates grand mean, 0.19 ± 0.03 µg/g, dry weight) were significantly lower than found within Suisun Bay (*Corbicula* sp., range of means, 3.9 to 5.2 µg/g dry weight and particulates range of grand means 0.23 to 0.53 µg/g dry weight); and similar to concentrations found in the un-enriched Tuolumne River, which drains the selenium-poor geologic units of the eastern San Joaquin Valley. No systematic selenium studies have been done in the Delta after San Joaquin River inflows to the Delta increased in the mid-1990s. The lack of study of Delta wetlands or shallow waters leaves open the question of whether selenium can be sequestered there, at least in some locations.

Particulate selenium in the existing length of the San Luis Drain

Transport, re-suspension, and re-oxidation of particulate material from the existing portion of the San Luis Drain, if extended, might also be a source of bioavailable particulate selenium to the Bay-Delta. Transformation of dissolved Se(VI) into particulate selenium has been demonstrated within the existing San Luis Drain. Early surveys done when the San Luis Drain was conveying drainage from the Westlands subarea to Kesterson National Wildlife Refuge determined a maximum sediment selenium concentration of 210 µg/g dry weight and an average of 84 µg/g dry weight in the San Luis Drain (Presser and others, 1996; appendix E, table E1). A compilation of data from surveys in 1994, after the Grassland Bypass Channel Project had begun, showed a maximum of 110 µg/g dry weight and an average of 44 µg/g dry weight in San Luis Drain sediment samples (appendix E, table E1). In whole core samples collected in 1997 from the San Luis Drain, the range of selenium concentrations was 2.9 to 100 µg/g with a mean of 30 µg/g dry weight (USBR and others, 1998). The elevated selenium concentrations and the wide range of concentrations documented in bed sediment of the San Luis Drain are consistent with observations from wetlands (including Kesterson Reservoir) where microbial dissimilatory reduction and biotransformation by primary producers stripped dissolved selenium from the water and converted it to particulate Se(0) and particulate Se(-II). Martens and Suarez (1997) showed that selenium in San Luis Drain sediment was probably about 90 percent elemental selenium, 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 selenium to particulate form (Presser and others, 1996; Presser and Piper, 1998). Re-suspension and transport of sediments from the San Luis Drain, therefore, must be considered as a source of selenium for the San Joaquin River, deserving of further study. Similarly, re-suspension of sediments in a San Luis Drain extension to the Bay-Delta could provide a direct source of highly contaminated particulate selenium to the Bay-Delta. The hydraulic residence time of the North Bay at low flows is about 60 days (Walters and others, 1985). Substantial oxidation of Se(0) could occur if fine particles and plant detritus generated in the San Luis Drain were transported to the Bay-Delta. Elemental selenium 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 a discharge point for a San Luis Drain extension or within sediments deposited within the San Luis Drain 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 San Luis Drain into Kesterson National Wildlife Refuge showed that selenium 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 selenium 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 and others, 1996)

Sedimentary selenium in Suisun Bay and San Pablo Bay

Transformation of selenium in wetlands in the Bay-Delta has not been well studied, nor have surveys of marsh sediments been done systematically. Zawislanski and McGrath (1997) reported concentrations of 1.0 to 1.25 µg/g dry weight in the sediments of a marsh on Carquinez Strait. Concentrations were similar in core samples collected down to 15 centimeters depth in the sediment. Using a range of dissolved concentrations in Carquinez Strait of 0.1 to 0.3 µg/L, the K_d for the marsh sediments ranges from 3.33×10^3 to 1.25×10^4. Zawislanski and McGrath (1997) also reported pore water concentrations of 2 to 10 µg/L, but further verification of such elevated values is necessary.

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

Zawislanski and McGrath (1997) reported selenium concentrations of 0.5 to 1.0 µg/g dry weight in mudflat sediments adjacent to a marsh in Carquinez Strait. Johns and others (1988) found mean concentrations of 0.31 µg/g dry weight in repeated analyses of sediments (fine-grained oxidized surface sediments, <100 µm) from four locations in Suisun Bay in the late 1984 to 1986. Concentrations in New York Slough, where the San Joaquin River enters Suisun Bay, were the highest in the region (0.53 ± 0.28 µg/g dry weight) and varied, the most widely of any station, from 0.2 to 1.0 µg/g dry weight. Recent studies by Cutter and Cutter (2004) and Doblin and others (2006) show results across a range similar to those reported by Johns and others (1988). In summary, concentrations of selenium in fine-grained Suisun Bay sediments are about 0.3 to 0.5 µg/g dry weight and median concentrations of dissolved selenium are 0.2 µg/L. These data show that the K_d is about 1.5 to 2.5×10^3, 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 selenium is well known and is especially important in determining exposures of detrital and filter-feeding consumer organisms. Selenium concentrations per unit mass suspended material exceed concentrations in bed sediments, based on several analyses conducted in April and September 1986 (Cutter, 1989); June 1995; and October 1996. Selenium concentrations in suspended material can vary widely.

- In April 1986, after an episode of extremely high river inflow, the maximum concentration of particulate selenium near Carquinez Strait was 0.64 µg/g dry weight, with an average concentration throughout the North Bay of 0.33 µg/g dry weight.

- In September 1986, during low inflows, the concentration of particulate selenium averaged 0.75 µg/g dry weight, with a maximum of about 1.25 µg/g dry weight. The particulate selenium concentrations were about 5×10^3 to 1×10^4 greater than the concentration per unit mass dissolved in the water column.

- In June 1995, during a prolonged period of very high inflows, particulate selenium concentrations ranged from 0.53 to 0.99 µg/g dry weight, with an average concentration among six samples of 0.68 µg/g dry weight. The K_d for median concentrations in this sampling was:
  [750 µg/kg dry weight] ÷ [0.075 µg/L] = 1×10^4.

- In October 1996, during low flows, particulate selenium concentrations were more than twice the concentrations in September 1986 (fig. 12). A concentration of about 7.70 µg/g dry weight was observed in suspended material in the Sacramento River channel at Rio Vista and 3.57 µg/g dry weight was found in the San Joaquin River channel. The two are interconnected at that time of year, so the San Joaquin River was the likely source of this material. Concentrations declined down the estuary, further suggesting a delta/riverine source. Elsewhere in the Bay-Delta, suspended material selenium concentrations were about 1.54 to 2.51 µg/g dry weight, with an average concentration in eight bay samples of 1.98 µg/g dry weight [more than two times higher than the mean (0.75 µg/g dry weight) in September 1986]. The K_d's for the median Suisun Bay selenium concentrations for the October 1996 survey were therefore:
  [2,100 µg/kg dry weight] ÷ [0.18 µg/L] = 1.17×10^4
  For the landward sites, highly elevated particulate concentrations yielded a K_d of:
  [5,600 µg/g dry weight] ÷ [0.18 µg/L] = 3.1×10^4.

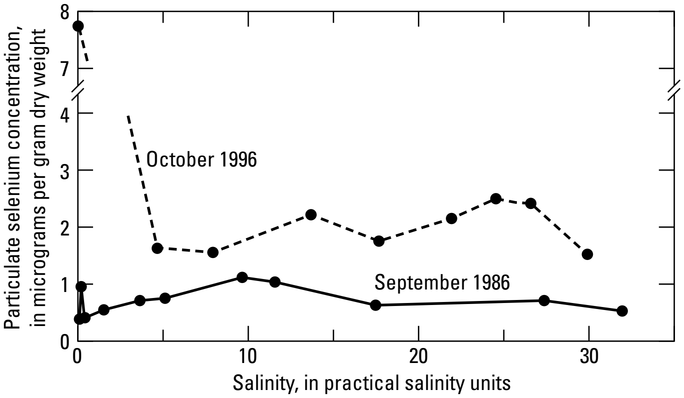

Figure 12. Particulate selenium profiles as a function of salinity in the Bay-Delta during high and low flow seasons in 1986 (9/86) and in 1996 (10/96).

Summary

Concentrations >1 µg/g dry weight in suspended materials are common and concentrations as high as 7.7 µg/g dry weight are observed in a few instances. The sources and frequency of the highest concentrations are not clear. K_d's in these surveys are consistently 1×10^4. 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 concentrations of selenium in suspended and sedimentary material and the differences in K_d's between these two reservoirs of selenium. Time-intensive studies and continued assessment of the sources of the highest selenium concentrations transported in suspended material to the Bay-Delta also are needed.

Bioaccumulation of Selenium by Invertebrates

Processes

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

- direct uptake of dissolved selenium;

- primary producers taking up selenium and they themselves being consumed by animals: and/or

- direct uptake of detrital or sedimentary selenium enriched particles via filter-feeding or deposit feeding.

In laboratory studies of the mussel *Mytilus edulis*, dissolved selenite is the most bioavailable form of inorganic selenium taken up from solution, but the uptake rate is slow compared to many trace elements (Wang and others, 1996). Luoma and others (1992) showed that the uptake rate of dissolved selenite explained less than 5 percent of the tissue burden of selenium accumulated by the clam *Macoma balthica* at concentrations typical of the Bay-Delta. The role of dissolved organic selenides in selenium bioaccumulation is not as well understood as availability of inorganic selenium, 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 selenium (dissolved selenite plus dissolved organo-Se) by invertebrates is not as important as uptake from diet (Luoma and others, 1992; Lemly, 1993a). Dissolved selenium speciation strongly influences uptake by primary producers (such as 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 about 10^4 or 10^5 (see, for example, 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; Wrench and Campbell, 1981), which are then transferred to the next trophic level with great efficiency. Assimilation efficiencies for phytoplankton-associated selenium range from 55 to 90 percent among different invertebrates (see, for example, Reinfelder and others, 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 and others, 1996; Luoma and others, 1992). For example, Luoma and others (1992) studied uptake of particulate elemental selenium produced from the microbial reduction of ^{75}Se-selenate *M. balthica*. The particulate Se(0) was formed by simulating the biogeochemical transformation process thought to be predominant in wetlands. The assimilation efficiency of elemental selenium was 22 percent by this bivalve.

Selenium in Invertebrates from the Bay-Delta

Fish and birds are the two taxa of greatest concern (the most sensitive) with regard to selenium contamination (Ohlendorf and others, 1989a; Skorupa, 1998c; Hamilton, 2004). 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 selenium. Consumer species such as bivalves, polychaetes, amphipods, or zooplankton can be practical to employ as resident bioindicators of selenium exposure (Phillips and Rainbow, 1993; Brown and Luoma, 1995b; Luoma and Rainbow, 2005). As discussed below, predators with the highest tissue concentrations of selenium in the Bay-Delta are benthivores that consume bivalves in their diet. Therefore, the most relevant bioindicators for these sensitive predator species are bivalves.

Interpretations are least ambiguous when selenium 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 source geologic units are not selenium-enriched, if no anthropogenic sources of selenium are known, and if concentrations in the indicator organism are in the lowest quartile of all available data. Concentrations of 1.70 to 2.66 µg/g dry weight were reported 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 and others (1988) found a mean reference concentration and 95 percent confidence limits of 3.08 ± 0.28 µg/g dry weight in *C. fluminea* from apparently uncontaminated sites near Clifton Court Forebay and in the Tuolomne River (fig. 13a).

Bivalves from the Bay-Delta have elevated selenium concentrations compared to these reference sites (Risebrough and others, 1977; Johns and others, 1988; Urquhart and Regalado, 1991) (fig. 13a). Risebrough and others (1977) reported concentrations of 10.0 to 11.4 µg/g dry weight in a single deployment of transplanted mussels (*Mytilus sp.*) in Carquinez Strait, and concentrations of 5.0 to 7.4 µg/g dry weight near Mare Island in Suisun Bay. Anderlini and others (1975) reported concentrations of 4.5 to 6.7 µg/g dry weight in the clam *M. balthica* near Mare Island in 1974. Although done more than 20 years ago, both these studies analyzed their samples by neutron activation, which is a relatively insensitive but reliable analytical technique. Johns and others (1988) collected *C. fluminea* from resident populations at six locations in Suisun Bay, between January 1985 and October 1986. Figure 13a 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 and others (1988). The mean concentration and 95 percent confidence limits among the Suisun Bay data was 5.08 ± 0.17 µg/g dry weight, significantly different than the reference values ($p<0.001$). These historic data show that the habitat in Carquinez Strait was contaminated twofold or more with selenium compared to reasonable reference locations, and that contamination was present since at least 1974.

In 1986, the bivalve *P. 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 and others, 1990). Figure 13b shows the *C. fluminea* reference site distribution and the frequency distribution of selenium among 62 composite samples of *P. amurensis* collected from Carquinez Strait between May 1995 and June 1997 (Linville and others, 2002). The mean concentration and 95 percent confidence limits among all data for *P. amurensis* was 12.94 ± 0.75 µg/g dry weight. A wide distribution of concentrations was also observed, reflecting substantial temporal variability.

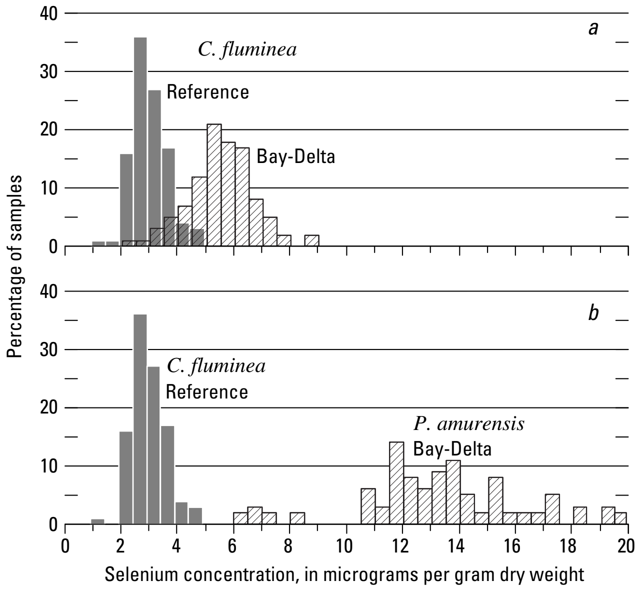

Figure 13. Frequency distributions of selenium concentrations in (*a*) composite samples of *C. fluminea* from references sites (see text for definition) and from Carquinez Strait collected between January 1985 and October 1986; and (*b*) composite samples of *P. amurensis* from reference sites (see text for definition) and from Carquinez Strait collected between May 1995 and June 1997.

Thus, the mean concentration of selenium in the dominant resident bivalve in Suisun Bay (*C. fluminea* in 1985–86 compared to *P. amurensis* in 1996) (fig. 14) has more than doubled since 1985–86. It is therefore likely that the total amount of selenium exposure of birds and fish that feed on bivalves has similarly doubled. The 1995–97 mean concentration in *P. amurensis* exceeds a dietary guideline with a high certainty of producing adverse effects in predators (see later discussion). During 1995–97, 32 percent of *P. amurensis* samples from Carquinez Strait contained selenium > 15 µg/g dry weight (Linville and others, 2002), thus creating an even greater potential for biotic consequences during some times of the year.

Selenium concentrations in *P. amurensis* from Carquinez Strait vary seasonally (fig. 14). Concentrations varied approximately threefold with time during 1995–97. The highest concentrations were observed in October 1996 (20 ± 1 µg/g dry weight) and the lowest concentrations were observed in May 1995 (7.13 ± 0.34 µg/g) and May 1997 (6.2 ± 0.2 µg/g). The changes in concentrations coincided with seasonal changes in mean monthly river inflows to the North Bay. The lowest concentrations occurred after two episodes of highest river inflows. The greatest increase in selenium occurred after prolonged periods of low inflow. Inflows from the San Joaquin River and/or inflow-driven differences in residence times of local waters also could be important, because the highest ratios of San Joaquin River to total Delta outflow occur in the fall (figs. 8 and 9).

An extensive spatial survey was done in October 1996 to determine how concentrations of selenium in *P. amurensis* compare among different locations in the North Bay. Selenium concentrations were determined in replicate composite samples of *P. amurensis* at 22 locations (Brown and Luoma, 1995a; Linville and others, 2002) (fig. 15). The October 1996 sampling included an extensive investigation of 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 and others (1988). Among the stations, the highest concentrations of selenium were found in resident *P. amurensis* located (1) in Carquinez Strait; (2) in the deeper, westward channel of Suisun Bay; and (3) towards the mouth of the San Joaquin River. 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 selenium concentrations were found in Grizzly Bay, in particular in association with inflows of Sacramento River water through a location called Suisun Cutoff.

Summary of Exposure

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

- Selenium enrichment in primary consumer species (bivalves) has been evident in Suisun Bay since the 1970s.
- The spatial pattern of historic contamination is consistent with an origin from refinery effluents (as shown by water column analyses).

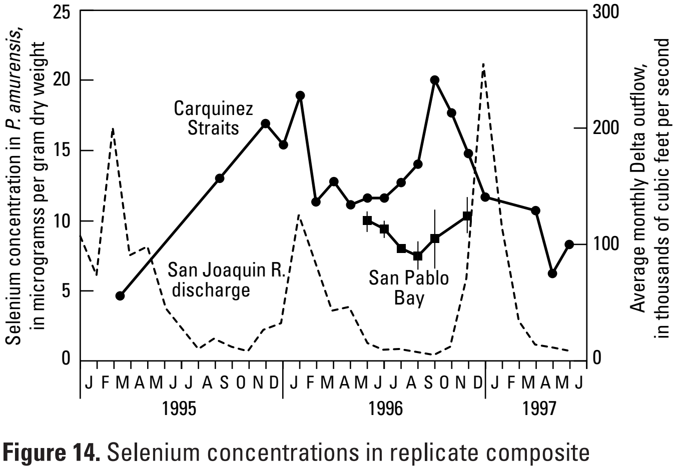

Figure 14. Selenium concentrations in replicate composite samples of *P. amurensis* and Delta outflows on a monthly basis from 1995 through 1997

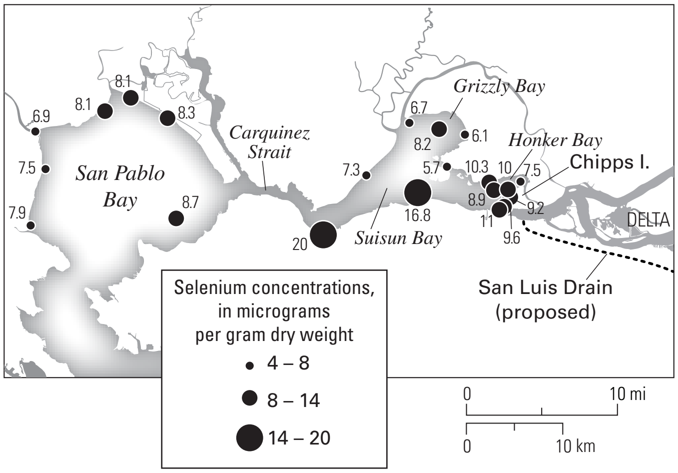

Figure 15. Selenium concentrations in replicate composite samples of *P. amurensis* at 21 locations in the Bay-Delta during October 1996.

- The highest selenium concentrations 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 others (2002). No systematic studies of selenium concentrations in clams are available since that time.

- Selenium enrichment was apparently spread through all of Suisun Bay and all of San Pablo Bay by 1996.

- Temporal variability was not significant in monthly samples of *C. fluminea* in 1985–86; but threefold seasonal variability in selenium 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, selenium concentrations in *P. amurensis* near Carquinez Strait exceed 10 µg/g dry weight in most months of the year (all months of some years), and 32 percent of values measured between October 1995 and June 1997, exceed 15 µg/g dry weight. Thus, concentrations in *P. amurensis* exceed a dietary guideline for predators that has a high certainty of producing adverse effects in predators (see later discussion).

- It is not yet clear whether the elevated selenium contamination in *P. amurensis* is unique to this species; represents greater selenium inputs (probably from the Delta and San Joaquin Valley through the San Joaquin River) than occurred historically; or both.

Modeling Selenium Bioaccumulation in the Bay-Delta: Dynamic Multi-Pathway Bioaccumulation (DYMBAM) Model

Bioavailability of selenium 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 (include consideration of geochemical form), biologically specific, and flexible in order to handle a variety of environmental circumstances. Predictions from a model should be verifiable in nature.

An approach used by USEPA (Peterson and Nebeker, 1992) uses the following simple ratio:

$$\text{Bioaccumulation} = \frac{[\text{concentration in organism}]}{[\text{concentration in environment}],}$$

where environmental concentrations are either those in water [bioaccumulation (BAF) or bioconcentration (BCF) factors] or sediment [sediment accumulation factor (BSAF)]. The flaw of this approach is that it does not allow consideration of the effects of speciation in water or of particulate material on bioaccumulation. Thus, bioaccumulation factors 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* (*DYMBAM) Model* uses different experimentally established uptake rates for different forms of dissolved and particulate selenium, along with environmental concentrations of these forms, to determine bioaccumulation in tissues (Luoma and others, 1992). The advantages of this approach are discussed extensively in Luoma and Fisher (1997), Schlekat and others (2002 and 2004), and Luoma and Rainbow (2005). One advantage for the Bay-Delta forecasts developed here is that bioaccumulation in prey (bivalves) can be derived for different speciation regimes. The speciation consideration is important because speciation will change as sources change, and relations with total selenium or individual species of selenium will also change (see, for example, San Francisco Bay Board, 1992a). Another substantial advantage of the approach is that predictions can be verified by comparison to analyses of selenium in tissues of resident species, such as clams. The *DYMBAM* model is used here in all forecasts of bioaccumulation in prey derived from different selenium load scenarios.

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

$$dC_m/dt = (I_f + I_w) - C_m(k_e + g) \qquad (1)$$

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

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

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

$$C_{m,ss} = I_f + I_w/k_e \tag{4}$$

if we assume that growth is not important. Mechanistically, the mathematics state that bioaccumulation in an organism 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 (equations 1 and 2). Gross influx can come from water or from food and is a species-specific function of the concentration of a bioavailable element.

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

$$I_f = FR \times C_f \times AE \tag{5}$$

where FR is feeding rate in grams of food per gram of tissue per day; C_f is concentration in food (particulate material in the case of bivalves) in grams of selenium per gram food (dry weight), and AE is assimilation efficiency of the food eaten by the animal. Influx rate from water can be broken into its components similarly (Wang and others, 1996), but because the influx rate from water was determined experimentally for specific species by Fowler and Benayoun (1976), Wang and others (1996), and Luoma and others (1992), the rate is employed directly here as µg selenium/g tissue per day.

From Reinfelder and others (1997), the ultimate concentration of selenium that a bivalve would bioaccumulate under each environmental condition can be calculated from:

$$C_{ss} = [I_w + (FR \times C_f \times AE)]/k_e \tag{6}$$

Bioaccumulation of Selenium by Predators

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

- Processes that affect selenium retention and inter-organ distribution are important considerations for fish and birds that range and feed widely over areas with varying selenium exposure pathways.
- Dietary exposure and, in most cases, with progressive biomagnification through the food web, is the pathway that leads to disproportionately large bioaccumulation of selenium in upper trophic levels.
- Some implications of dietary uptake are:
    - o waterborne selenium concentrations are poorly linked to predator bioaccumulation because environmental factors affect transformation of selenium and uptake by invertebrates;
    - o where data on predators is difficult to obtain directly, invertebrates may be the best indicator for monitoring predator exposures;
    - o a predator's choice of food, which varies widely among species, could result in some trophic pathways being more efficient accumulators of selenium 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 provide an elevated route of vertebrate exposure as compared to herbivorous species (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 selenium in fish. This study was at a reservoir (Belews Lake, North Carolina) contaminated by wastes from a coal-fired power plant (Cumbie and Van Horn, 1978). Lemly compared concentrations of selenium in bluegill and largemouth bass collected from the lake, with concentrations of selenium in those species when exposed to sublethal concentrations of selenium in water alone in a laboratory study. A lower concentration factor was found from water alone than from bioaccumulation through dietary plus waterborne sources. This finding was corroborated by the observation that piscivorous fish (fish that feed on other fish), at the highest trophic level, accumulated the most selenium in the lake. All piscivores and omnivores eventually succumbed to selenium poisoning, while a few lower trophic level fish survived. Other studies have since verified directly and indirectly the overwhelming importance of selenium bioaccumulation from food, as compared to direct uptake from water.

If the primary source of selenium to wildlife is dietary, then it should not be surprising that waterborne or dissolved selenium is an imprecise predictor of the selenium exposure of birds and fish (Luoma and others, 1992; Presser and others, 1994; Schlekat and others, 2002; Luoma and Rainbow, 2005). Differences in dissolved species, transformation to particulate form(s), particulate species, and invertebrate bioaccumulation all influence how waterborne selenium is transferred to predators. These processes are affected by the nature of the source and the environmental conditions in receiving waters (for example, selenium in agricultural drainage water can be in a different form than the selenium in industrial sources; selenium discharged to a wetland is transformed differently than selenium discharged to an estuarine water column). Physical processes such as hydraulic residence time also are important. Particulate transformation of selenium in a river (such as the San Joaquin River) may occur far downstream from the source; while transformations in a wetland or an estuary with a long residence time may occur near the source. Biological processes that affect exposure of a predator include differences among species in feeding, behavior, and physiology.

An example of the influence of confounding processes among these links can be found in data from the Bay-Delta watershed. Black-necked stilts (wading birds), averaged about the same exposure to selenium (20 to 30 µg/g dry weight found in eggs) at Chevron Marsh in the Bay-Delta as at Kesterson Reservoir (25 to 37 µg/g dry weight in eggs), but the source water in Chevron Marsh contained about 10 percent the concentration of selenium found at Kesterson Reservoir (maximums: 20 µg/L compared to 300 µg/L) (Skorupa, 1998a). The reason for the difference was that the transfer of selenium from water to aquatic invertebrates was greatly enhanced at Chevron, compared to Kesterson, because the source form of the element was selenite.

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

One repeated observation in contaminated ecosystems is that predator species differ in their bioaccumulation of selenium. 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 groups were probably too broad, however. In Lake Oltertjarn, Sweden, after treating the lake with selenite for two years, selenium tissue concentrations in northern pike (*Esox lucius*) averaged 4.6 µg/g dry weight, whereas in perch (*Perca fluviatilis*) the average was 23 µg/g dry weight (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 selenium concentrations, whereas pike ate water-column-feeding fish with low selenium concentrations.

Differences in selenium exposure among predators also seem to be the case in the Bay-Delta. Fish (such as white sturgeon, starry flounder, and probably Sacramento splittail) that ingest benthos, and especially bivalves, have higher selenium concentrations (see, for example, 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 selenium contamination. It is likely that the species experiencing the highest exposure of selenium are at the greatest risk of extinction or of population damage. It also should be remembered that biomagnification is sufficient to eliminate species at the top of the trophic structure, even when waterborne selenium concentrations are in the 2 to 5 µg/L range (Lemly, 1985, 1997b, d). Therefore, some selenium contaminated systems may already have lost vulnerable links in the food web, even though populations of some species remain. Study of systems with less extreme contamination may be one way to understand where those vulnerable links occur.

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

The Department of Fish and Game conducted extensive sampling of a variety of bird and fish species in the Bay-Delta between 1986 and 1990 through a *Selenium Verification Study* for the State Board (White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991). This effort was one of the most extensive surveys of selenium 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 selenium. The greatest differences between the two ecosystems occurred in bottom-feeding fish [such as English sole (*Parophrys vetulus*) with 3.05 ± 0.2 compared with 1.78 ± 0.2 µg/g dry weight in flesh, respectively; and starry flounder with 9.2 ± 2 compared with 3.6 µg/g dry weight in liver, respectively]. Although the sampling was limited in number, Dungeness crab from Suisun Bay contained a mean selenium concentration of 14 µg/g dry weight tissue, compared to a mean concentration of 5 µg/g dry weight tissue in Humboldt Bay. Selenium concentrations in Pacific herring (*Clupea pallasi*), speckled sanddab (*Citharichthys stigmaeus*) and longfin smelt (*Spirinchus thaleichthys*) were not different between the two ecosystems. Uptake of selenium by striped bass in the North Bay also did not appear problematic in samplings in 1986 (average, 1.3 to 1.9 µg/g dry weight) (Saiki and Palawski, 1990). Thus, some bottom-feeding fish bioaccumulated selenium in excess of the reference area, but fish (such as herring, striped bass) that were primarily herbivorous, or fed from the water column, showed little difference in selenium tissue concentrations between the two ecosystems.

The highest concentrations of selenium were found in white sturgeon in the Bay-Delta (fig. 16). 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 San Joaquin River (Kohlhorst and others, 1991). White sturgeon are voracious consumers of *P. amurensis*. This raises the possibility that selenium trophic transfer via bivalves is a critical pathway of selenium exposure in the Bay-Delta. If so, it would be expected that selenium concentrations in white sturgeon should probably have increased after *P. amurensis* invaded the estuary in 1986. In 1986, the average concentration of selenium in livers from ten white sturgeon was 9.2 ± 2.9 µg /g dry weight (White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991). In 1989–90, the average concentration of selenium in livers from 42 white sturgeon was 30 ± 21 µg/g dry weight. Although variability was high (as expected for animals that move over large areas), the average selenium 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 and others, 1997; Fairey and others, 1997; San Francisco Estuary Institute, 1999). The number of white sturgeon analyzed were many fewer than determined for

Table 12. Selenium concentrations in fish from the Bay-Delta (North Bay including Suisun, San Pablo, Grizzly and Honker Bays) and Humboldt Bay.

[Data from Selenium Verification Study: White and others (1987, 1988, 1989); Urquhart and Regalado (1991). Tissue data in dry weight; std. dev. = standard deviation; n = number of samples.]

Location (date) and species	Selenium (dry weight)								
	Flesh (µg/g)			Liver (µg/g)			Whole-body (µg/g)		
	Average	Std. dev.	n	Average	Std. dev.	n	Average	Std. dev.	n
North Bay (January –June, 1986)									
white sturgeon	7.8	3.1	10	9.2	2.9	10	–	–	–
English sole	3.0	0.2	4	–	–	–	–	–	–
starry flounder	4.6	1.0	7	9.2	2.2	7	–	–	–
longfin smelt	–	–	–	–	–	–	1.5	0.4	8
Pacific staghorn sculpin	2.5	0.2	8	6.7	1.0	8	–	–	–
Pacific herring	–	–	–	–	–	–	3.0	0.7	4
speckled sanddab	–	–	–	–	–	–	1.8	0.03	2
northern anchovy	–	–	–	–	–	–	2.1	0.08	4
yellowfin goby	–	–	–	–	–	–	2.4	0.2	7
North Bay (March–May, 1987)									
white sturgeon	10	3.7	13	–	–	–	–	–	–
North Bay (December, 1987 and January, 1988)									
white sturgeon	7.2	4.4	14	–	–	–	–	–	–
North Bay (February, 1989 to March, 1990)									
white sturgeon	15	11	62	30	21	42	–	–	–
yellowfin goby	2.0	–	1	4.3	–	1	3.1	–	1
Humboldt Bay (February and June, 1986)									
English sole	1.8	0.22	3	7.8	–	1	–	–	–
starry flounder	0.9	–	1	3.6	–	1	–	–	–
longfin smelt	–	–	–	–	–	–	1.2	0.08	2
Pacific staghorn sculpin	1.6	0.13	4	3.9	0.46	3	–	–	–
Pacific herring	1.6	0.08	2	–	–	–	4.5	–	1
speckled sanddab	–	–	–	–	–	–	1.6	0.3	4

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 selenium contamination of white sturgeon in the late 1990s.

The contrast is interesting between selenium concentrations in white sturgeon and those in striped bass, another major resource species in the system. Striped bass, like white sturgeon, are anadromous fish, 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 San Joaquin River downstream through San Pablo Bay. Some of their observations about selenium concentrations in whole-body samples of striped bass included:

- The highest selenium concentrations were found in the main channel of Mud Slough and in the San Joaquin River immediately downstream from Mud Slough.
- The mean selenium concentration among the six most contaminated sites was 5.3 µg/g dry weight.
- Selenium concentrations were low above Mud Slough and also downstream in the San Joaquin River, as tributary dilution increased (range of 1.03 to 2.9 µg/g dry weight in the lower San Joaquin River, below the Merced

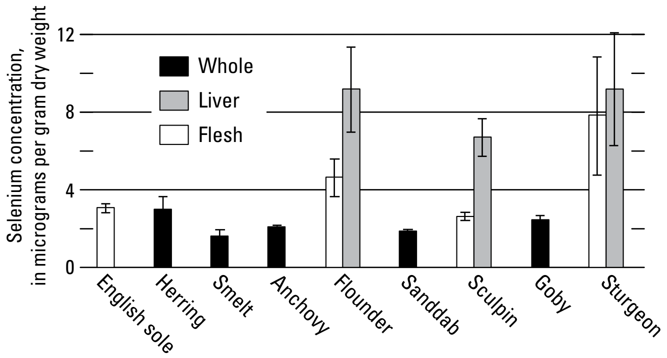

Figure 16. Average selenium concentrations in fish collected from the North Bay during 1986. (Data from White and others, 1987)

River). So bioaccumulation was responsive to expected inputs of contamination.

- Mean selenium concentrations in the North Bay were 1.3 to 1.9 µg/g dry weight. These values are at least fivefold lower than the average concentration in white sturgeon from the North Bay, at that time (table 12, when selenium in flesh is converted to selenium in whole-body samples).

In summary, striped bass do bioaccumulate more selenium in environments where more selenium is present. However, these animals are not exposed to as much selenium 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 selenium than are white sturgeon, suggesting that links between bioaccumulation and adverse effects need to be studied, perhaps comparatively, in these species.

Eleven species of waterfowl also were analyzed in the *Selenium Verification Study* (White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991) (fig. 17). 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, Gray Lodge Wildlife Area, and the Sacramento National Wildlife Refuge) showed the following average selenium concentrations in liver tissue: dabbling ducks, 3 to 8 µg/g dry weight; shorebirds, 4 to 12 µg/g dry weight; and cormorants 18 µg/g dry weight (White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991). Average concentrations in greater and lesser scaup liver were 9 µg/g dry weight and in surf scoter liver were 17 µg/g dry weight. These values are typical of uncontaminated areas elsewhere in the world, as well (Goede, 1994). Concentrations of selenium 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 percent higher in the Bay-Delta than in reference areas. Mean selenium concentrations in livers of American coot and scaup from Suisun Bay and San Pablo Bay were 2 to 4 times those in samples from reference areas. The highest concentrations of selenium in aquatic birds in the Bay-Delta were found in surf scoter (range 13 to 368; average 134 µg/g dry weight range in liver) from Suisun Bay and San Pablo Bay. Annual averages from Suisun Bay range from 80 to 240 µg/g dry weight 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/g dry weight). These concentrations also exceeded concentrations found in surf scoter from Morro Bay, the Central Bay and the South Bay (White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991). Concentrations in surf scoter livers from the North Bay were also two to threefold higher in 1988, 1989, and 1990, than in 1986.

Concentrations of selenium varied remarkably among bird species with different food preferences in San Pablo and Suisun Bay. The most contaminated birds (surf scoters) had selenium concentrations in their livers that were up to two orders of magnitude higher than the selenium concentrations in mallards and American bittern. Because of feeding habits, it seems that vegetarians exhibited some of the lowest selenium 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 and others, 1995;

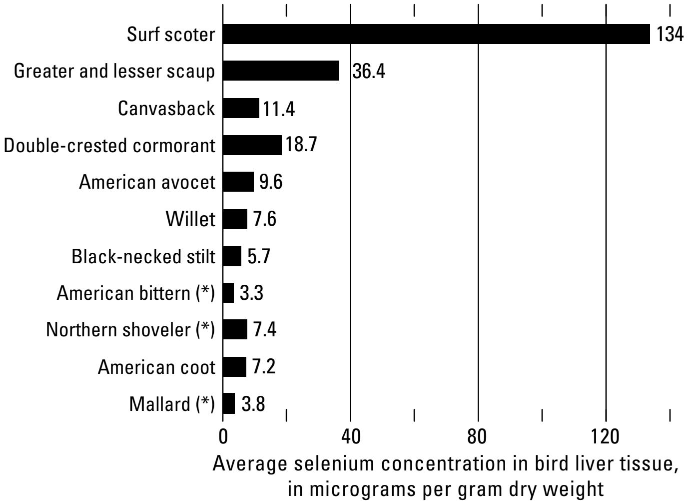

Figure 17. Average selenium concentrations in bird liver tissue collected from 1986 to 1990 in: (1) Suisun Bay and San Pablo Bay; and (2) Suisun Marsh (denoted by asterisk), a large area of brackish wetland located north of Suisun Bay (fig.2), not subject to the same direct selenium sources as Suisun Bay [Data from White and others, 1987; 1988; 1989; Urquhart and Regalado, 1991].

Hoffman and others, 1998). In general, scaup obtain about 40 percent of their diet from animal food sources compared to scoter, which obtain about 95 percent of their diet from animal food sources.

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

Effects of Selenium on Predators

Selenium is an essential element in animals necessary for the formation and proper functioning of glutathione peroxidase, an important antioxidant enzyme. The difference between required concentrations and toxic concentrations of this element is narrow compared to other toxins (see, for example, National Research Council, 1976; Luckey and Venugopal, 1977; Wilbur, 1983; Hodson and Hilton, 1983; Presser and Ohlendorf, 1987; Drainage Program, 1990b). In amounts just slightly above those need for nutrition, selenium is erroneously substituted for sulfur in selenium-containing amino acids (methionine and cysteine). This substitution disrupts the structure of proteins and enzymes, which results is malformations during critical stages of development and growth. In birds, reproductive failure (inviability of eggs) and/or teratogenesis (deformities in developing young) are early and dramatic manifestations. However, egg hatchability in birds has proven to be the more sensitive endpoint (Skorupa, 1998b and 1999). Effects endpoints in birds can be generally grouped in terms of sensitivity from least to greatest (adult mortality, juvenile mortality, teratogenesis, mass wasting in adults, embryo mortality, reduced juvenile growth, immunosuppresssion), although some endpoint have been studied more than others. In fish, reproductive impairment occurs to reduce production of viable eggs due to ovarian pathology in spawning females (necrotic and ruptured mature egg follicles) and post-hatch mortality due to metabolism of egg selenium by developing larval fish (teratogenic deformities and biochemical dysfunction) (Lemly, 2002). Hatchability of eggs in fish is not affected by elevated selenium. However, teratogenesis is induced when larval fish are relying on their attached yolk sac for nourishment and development. Once external feeding begins, selenium will not cause further deformities in the juvenile fish. Thus, the vulnerable pathway is mother to egg to developing larvae and fry. Further detail is added to interpretation of effects by guidance measured against either an effect concentration or lethal concentration and its relation to the percentage of effects tolerated (tables 13, 14, and 15).

Deformities in themselves may not always be lethal, but they lower the probability that a 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 in fish it is important to focus on newly emerging larvae and fry.

In addition to the sensitivity of life stages, studies of birds demonstrate the sensitivity of different species and forms of dietary selenium. Selenomethionine is considered the relevant dietary supplement (Heinz and Hoffman, 1996; Heinz and others, 1996 a, b). Diets supplemented with inorganic selenium result in selenium concentrations in eggs that are only 0.1 to 0.18 times dietary concentrations, whereas those supplemented with selenomethionine are in the range of 1 to 4 times dietary selenium (Heinz and others, 1989; Ohlendorf, 1989). Field studies of ducks, stilts, and avocets comprise the largest database (Skorupa, 1998a, b), with the order of sensitivity (duck > stilt > avocet) helping to determine protective guidelines on both a national scale and site-specific scale.

O'Toole and Raisbeck (1998) in studies of the effects of selenium at Kesterson National Wildlife Refuge 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).

Other considerations in determinative studies for interpretation of guidelines include use of eggs as a metric. Selenium concentrations in eggs reflect changes in reproductive success and thus are a sensitive indicator of biological response (Lemly 2002). Bird eggs especially provide unbiased exposure-response data in field studies because the health of embryo inside does not influence a scientist's probability of sampling the egg (Skorupa, 1998b). Eggs also are not subject to survivor bias; that is, samples of free-living birds and fish are self-selected to be insensitive (biased) measures of biotic response because only survivors (live specimens) are sampled. For example, complete reproductive failure can occur in the absence of observable toxic effects on adults. Adult fish can survive and appear healthy despite the fact that extensive reproductive failure is occurring (that is, toxicity in fish can be invisible) (Lemly 2002b). Committing type II error (acceptance of a false negative) also can be common in bird studies, if eggs are not collected. Bird populations can be abundant and diverse at the time of sampling, but without demonstration of embryotoxic effects through use of bird egg selenium concentrations, these exposure surveys, not exposure-response studies, have a low power to detect a biotic response (Skorupa, 1998b).

Additionally, most field studies have been completed in off-stream environments (ponds, lakes, reservoirs) that in terms of fish have dealt with demographically closed populations (Skorupa, 1998b). Here, population collapse is relatively easy to detect as a response. In in-stream studies of effects, measurements can be taken on biased survivors from demographically open populations replenished by outside immigrants. Thus, such studies can report the counterintuitive combination of elevated levels of selenium in fish and what is viewed as normally abundant and diverse fish assemblages. These type studies are of low statistical power for detecting toxicity because they neither meet the closed-population or unbiased exposure-response sampling criteria.

Community simplification (including local extinction of some species) is ultimately the result of excessive selenium contamination. Sixteen of the twenty fish species that originally inhabited Belews Lake disappeared when selenium 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 selenium contamination was introduced (Saiki, 1986; Saiki and Lowe, 1987; Saiki and others, 1991; Skorupa, 1998a). Hamilton (1999) presented the hypothesis that selenium 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 it continues to inhibit their recovery. Hamilton (1999) concluded that reservoir construction and introduction of exotic species have undoubtedly contributed to the decline of endangered fish species in the Colorado River, but that selenium also must be included as an important contributing factor. Hamilton (1999) cited four lines of evidence linking selenium 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 discharges, which began in the 1890s;
- 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 (such as 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.

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 selenium cannot be ignored as an issue that can inhibit accomplishment of that goal.

Fish eggs (unfertilized in a female or fertilized), developmental stages of fish (alevins or yolk-sac fry, larvae), and offspring of live-bearing fish species collected in the field also are valuable as unbiased measures of reproductive status (Lemly, 2002). A combination of field collected eggs and laboratory fertilization is productive in detecting and quantifying effects based on field diets. Sensitive life-stages such as larvae, fry, and juveniles can be studied. Holm and others (2003), Palace and others (2004), and Muscatello and Janz (2004) have studied effects in coal and uranium mining areas of Canada using this technique for rainbow trout (*Oncorhynchus mykiss*), brook trout (*Salvelinus fontinalis*), northern pike (*Esox lucius*), and white sucker (*Catostomus commersoni*). Hamilton and others (2005b) also used this technique with razorback sucker studies related to selenium contamination in the Colorado River basin. Effects studied were fertilization rate, time to hatch, percent hatchability, time to swim-up, and frequency of deformities. Care must be taken in interpretation of larval fish studies in that rapid growth is occurring that may lead to large variations in tissue selenium concentrations.

Selenium concentrations in food and in tissues (tables 13, 14, and 15) both have been employed to evaluate how the exposure of selenium experienced by an animal is linked to effects on reproduction or teratogenesis. Links 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, selenium 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. Compiled studies reported for determining concentration guidelines (tables 13, 14, and 15) show the many considerations (selection of species, endpoint, life-stage, exposure mechanism, effect level, translation to dry weight) influence effect studies and their outcomes.

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

Fish

Threshold and concern levels encompass a range of dietary selenium of 2 to 8 µg/g dry weight, with effects a certainty if the upper limit is exceeded (table 13). The range of concern has narrowed to 2 to 5 µg/g dry weight because of studies involving sensitive species, life-stages, and endpoints (table 13). Concentrations of selenium > 3 µg/g dry weight in the diet of fish result in deposition of elevated concentrations in developing eggs, particularly in the yolk (Lemly, 2002). Studies of effects in sensitive life stages and during increased stress (reduced temperatures) show a range in diet of 4.6 to 5.2 µg/g dry weight (table 13). Terata in fry of recovering fish were recorded at diets of 2 to 5 µg/g dry weight at Belews Lake (Lemly, 1993b; 1997b). Dietary selenium concentrations of 5 to 20 µg/g dry weight load eggs beyond teratogenic guidelines (Lemly, 1997a, 1998a, and 2002). Complete reproductive failure is associated with dietary concentration of 30 to 35 µg/g dry weight (Skorupa, 1998b; Woock and others, 1987; Coyle and others, 1993). Extinctions of fish species occurred

Table 13. Dietary selenium exposure guidelines for fish and selenium concentrations in the most abundant benthic prey organism in the North Bay (Suisun Bay and San Pablo Bay).

[Focus is on sensitive endpoints and life stages; diet as selenomethionine; and parental exposure. Values are in dry weight with conversion from wet weight and percent moisture given, if applicable. The example of Kesterson Reservoir, California also applies to aquatic birds.]

Diet (µg/g selenium dry weight)	Approach or site	Effects and Species	Reference(s)
2–4	Synthesis	Threshold ranges for reproductive failure	Engberg and others, 1998
3	Synthesis	Maximum allowable concentrations (protective of reproduction)	Lemly, 2002a
2–4	Synthesis	Diagnostic residues; ecosystem contamination sufficient to cause reproductive impairment	Lemly, 1998b
3–7	Synthesis	Range of concern; toxicological and reproductive effects a certainty if upper limit exceeded; impaired development and survival in larval fish.	Engberg and others, 1998; USBR and others 2004; Hamilton and others, 1996, 2004; Presser and others, 2004
3–8	Synthesis	Reproductive impairment threshold (LOAEL)[a] via lethal larval exposure (salmon, bluegill, razorback sucker)	Skorupa, 1998b
2–5.9	Belews Lake, North Carolina	Teratogenesis in fry of four recovering fish species [common carp (*Cyprinus carpio*), bluegill (*Lepomis macrochirus*), largemouth bass (*Micropterus salmoides*), mosquitofish (*Gambusia affinis*)]	Lemly, 1997b; 2002a; 2002b
4.6	Lab	Mortality in razorback sucker (*Xyrauchen texanus*) larvae	Hamilton, 2004; Hamilton and others, 2002, 2005d
3.2–5.3	Lab	Reduced growth in chinook salmon (*Oncorhynchus tshawytscha*) swim-up larvae	Hamilton and others, 1990
5.1	Lab	40% overwinter mortality (winter stress) in juvenile bluegill	Lemly, 1993b
5–20	Synthesis	Sufficient to load eggs beyond teratogenic threshold	Lemly, 1997a, 1998a, 2002
30–35	Synthesis	Complete reproductive failure (100% effect level) in bluegill; parental exposure	Skorupa 1998a based on Coyle and others, 1993; Woock and others, 1987
15–57	Belews Lake, North Carolina (1973–84)	Massive poisoning of fish community (16 of 20 species disappeared; two species rendered sterile, but persisted as aging adults; one occasionally re-colonized as adults; and one unaffected; deformities in survivors; some recovery after selenium)	Cumbie and Van Horn, 1978; Lemly, 1985; 1997b; 1998a
155–290	Kesterson Reservoir (pond 2), California	Massive poisoning of fish and birds and deformities in coots, grebes, ducks, and stilts.	Saiki and Lowe, 1987; Ohlendorf, 1989; Presser and Ohlendorf, 1987.
4–20	North Bay 1985–86 and 1995–96	Range in predominant bivalve as diet for Bay-Delta predators such as sturgeon, scoter, and scaup	White and others, 1987; 1988; 1989; Urquhart and Regalado, 1991; Johns and others, 1988; Linville and others, 2002

[a] LOAEL = lowest observable adverse effect level.

in Belews Lake, when selenium concentrations in invertebrates were in the concentration range of 15 to 57 µg/g dry weight. Concentrations in invertebrates in Kesterson National Wildlife Refuge were > 100 µg/g dry weight in the presence of selenium-induced bird deformities and disappearance of most species of fish (Saiki and Lowe, 1987; Presser and Ohlendorf, 1987; Ohlendorf, 1989).

Birds

Concern levels range from 2 to 7 µg/g dry weight in diet (table 15). The range of concern has narrowed to 2 to 5 µg/g dry because of studies involving sensitive species, life-stages, and endpoints (table 15). Lemly rates 2 to 4 µg/g dry weight as a diagnostic residue range that indicates ecosystem contamination sufficient to cause reproductive impairment. Heinz and others (1989) showed that selenium in eggs of mallards (experimental exposure) was closely related to hen's dietary exposure to selenium (fed seleno-methionine). Average egg concentrations were 2.5 to 4.0 times dietary concentrations. Ohlendorf (1989) reported that bird eggs generally contain 1 to 3 times the dietary selenium of breeding females. Skorupa and Ohlendorf (1991) concluded that, if assimilation of selenium in the wild is similar to seleno-methionine in the laboratory, then dietary selenium of 5 µg/g dry weight would yield 15 µg/g dry weight in eggs. This level in eggs was the lowest mean concentration associated with embryo teratogenesis at Kesterson Reservoir.

Heinz and others (1989) and Heinz (1996) cited 3.3 µg/g dry weight in diet as threshold for reproductive impairment from a synthesis of data. Ohlendorf (1989) concluded that hatchability of eggs is reduced when dietary concentrations are 6 to 9 µg/g dry weight. In a compilation of data for mallards, 4.87 µg/g dry weight in diet was associated with a 10 percent hatchability effect (Ohlendorf, 2003). The upper confidence level was 5.74 mg/g dry weight and lower confidence level was 3.56 mg/g dry weight (table 15). Stanley and others (1996) showed that 7.7 µg/g dry weight in diet was associated with a range of effects in mallards (reduced hatching success, reduced growth and weight in hatchlings, reduced number of surviving ducklings produced per female). Based on a synthesis of data, Stanley and others (1996), concluded that the threshold range in mallards for teratogenesis and mortality in ducklings (both less sensitive endpoints) was 7.7 to 8.8 µg/g dry weight. Adverse effects on body condition (thought to be an endpoint of intermediate sensitivity) of male American kestrels (*Falco sparverius*) occurred at 6 µg/g dry weight (Yamamoto and Santolo, 2000). Seleno-methionine in food at concentrations of 16 µg/g (as selenium) caused complete reproductive failure in mallards (Heinz and others, 1989).

So, as with fish, concentrations of 2 to 6 µg/g dry weight in food encompass critical dietary levels for birds. As mentioned previously, a small range encompasses what level is nutritional and what level represents a certainty of effects if that limit is exceeded (that is, an upper limit essential for ensuring ecosystem health). Thus, field and laboratory studies all suggest that selenium concentrations typical of bivalves in Suisun Bay and San Pablo Bay (6 to 20 µg/g, table 13 and figs. 13 through 15) are beyond guidelines of selenium concentrations in food that have a high degree of certainty of causing 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 selenium in fish to reproductive or teratogenic effects (table 14). Reproduction has the advantage of being a sensitive endpoint to study. But, other environmental factors as well as selenium 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 contaminant-caused changes are more likely to be uni-directional with exposure to the contaminant. No long-term studies are available from the Bay-Delta, however. Teratogenesis is a less sensitive measure of selenium effects, but has the very attractive advantage of being a more selenium-specific outcome (many fewer factors cause teratogenesis than affect reproductive success).

The range of concern for selenium concentrations in whole-body fish tissue has narrowed from 4 to 12 µg/g dry weight to 1.5 to 6 µg/g dry weight because of studies involving sensitive species, life-stages, and endpoints (table 14). This range of whole-body values translates to 1.2 to 4.6 µg/g dry weight in muscle using a translation factor of 0.83. Although a consensus has not been reached on this factor for selenium, the overall lowering of the concentration in flesh is due to the exclusion from the sample of organs such as liver which contain elevated concentrations of selenium compared to flesh. The range of concern in fish eggs is 5 to 10 µg/g dry weight and in liver 12 to 15 µg/g dry weight. Deformities increase rapidly in prevalence once selenium in fish eggs exceeds 10 µg/g dry weight. 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 guidance 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 selenium concentration found in 62 samples of white sturgeon muscle was 15 µg/g dry weight and in 42 samples of liver was 30 µg/g dry weight (table 12 and fig. 16). Both means are above the range of guidance concentrations at which reproductive effects and deformities in larvae and fry are likely to occur (table 14). Some concentrations (range 6 to 80 µg/g, dry weight liver; 2 to 50 µg/g, dry weight muscle) in individual fish exceed tissue guidelines for producing extinction of fish species. However, the relation of reproduction and selenium-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 selenium concentrations in ovaries and egg yolk components are above guidelines for effects (Kroll and Doroshov, 1991) (table 14).

Birds

Guidelines for selenium in tissue of birds are not too different from those in tissues of fish. The range of concern for selenium concentrations in egg tissue in birds is from 3 to 6 µg/g dry weight (table 15). Heinz (1996) stated that the embryo is the avian life stage most sensitive to selenium poisoning. Skorupa (1998 a, b, c) concluded that selenium concentrations in eggs are a good choice for a risk metric to determine avian embryonic exposure and response. Hatchability is more sensitive an endpoint 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,

Table 14. Tissue selenium guidelines for fish and selenium concentrations in tissues and eggs of white sturgeon from the North Bay (Suisun, San Pablo, Grizzly, and Honker Bays).

[Focus is on sensitive endpoints and life stages; and parental exposure. Values are in dry weight with conversion from wet weight and percent moisture given, if applicable.]

Fish tissue (µg/g selenium dry weight)	Approach or site	Effects, species, or North Bay fish	Reference(s)
4–12 (whole-body)	Synthesis	Range of concern; toxicological and reproductive effects a certainty if upper limit exceeded.	Engberg and others, 1998
4 (whole-body) 8 (muscle) 12 (liver) 10 (egg)	Synthesis	Maximum allowable concentrations (protective of reproduction)	Lemly, 2002a
5–7 (whole-body) 6–8 (muscle) 15–20 (liver) 5–10 (egg) 8–12 (larvae and fry)	Synthesis	Diagnostic residues for reproductive impairment (deformity or mortality of larvae/fry); applies to centrarchids, fathead minnows, salmonids, percichthyids	Lemly, 1998b
4–6 (whole-body) 7–13 (gonad/egg)	Synthesis	Reproductive impairment (10% effect level) in sensitive species (perch, bluegill, salmon)	Skorupa, 1998b; Presser and others, 2004
4–6.5 (whole-body)	Lab and synthesis	Growth and survival (swim-up Chinook salmon larvae)	Hamilton and others., 1990; Hamilton, 2002 and 2003
3.6–8.7 (whole-body)	Field	Survival (razorback sucker larvae)	Hamilton and others, 1996, 2005c, d; Hamilton 2002, 2004
5.85 (whole-body)	Lab	40% overwinter mortality in juvenile bluegill (winter stress)	Lemly, 1993b
6 coldwater (whole-body) 9 warmwater (whole-body) 17 (ovary)	Synthesis	Recommended toxicity guidelines (10% effect level)	DeForest and others, 1999
10 (egg); 6–17 (egg)	Synthesis	Rapid rise in deformities (terata) for centrarchids	Lemly, 1993b
12.5 (egg based on 52% moisture) 4.3 (muscle translation)	Field (eggs and milt) Lab (rearing of fish)	Rapid rise in edema and deformities in rainbow trout (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*) fry (parental exposure)	Holm and others, 2003
18–22 (egg based on 52% moisture); 6.4–7.6 (muscle translation)	Field (eggs and milt) Lab (rearing of fish)	Range of 15% effect level (edema, skeletal or craniofacial deformities) in rainbow trout swim-up fry	Holm and others, 2005
40–125 (whole-body) 25–200 (muscle) 20–170 (egg)	Field	16 fish species extirpated; 10–70% rates of teratogenesis	Cumbie and Van Horn, 1978; Lemly, 1985, 1997b, 1998a, 2002
30 (liver, average; n=42; range 6–80) 15 (flesh, average; n=62; range 2–50)	North Bay (1989–90)	white sturgeon (*Acipenser transmontaus*)	Urquhart and Regalado, 1991
3–29 (ovary); 5–9 (plasma) 3–90 (egg yolk components)	North Bay (no date)	white sturgeon	Kroll and Doroshov, 1991

Ohlendorf and others (1986) showed a strong correlation between embryonic selenium exposure and embryonic viability (hatchability). Hatching failure started increasing rapidly above 10 µg/g dry weight egg. Skorupa (1998a) suggested the critical exposure concentration causing reduced hatchability, for sensitive birds, is 6 to 7 µg/g dry weight in eggs. His conclusion is based 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 threshold (3 percent effect level) of hatchability in a sensitive species of aquatic bird (stilt) is 6 µg/g dry weight (Skorupa, 1998a,b; 1999). Ohlendorf (2003) calculated a 10 percent effect concentration of 12.5 µg/g dry weight in eggs from a compilation of data from laboratory studies of mallards. The upper confidence level was 16.5 µg/g dry weight and lower confidence level was 6.4 µg/g dry weight. Data from the coal mining areas of Canada concerning American dippers and spotted sandpipers show a 15 to 16 percent depression in egg viability at 5.1 and 8.2 µg/g dry weight egg selenium.

Hepatic (liver) concentrations may be a less precise indicator of pathological conditions than are egg concentrations (table 15). Selenium concentrations quickly buildup or decline in the liver when birds are introduced to or removed from a selenium-contaminated diet (Heinz, 1996). Using selenium concentrations in adult females to predict reproductive impairment in birds is not as good as using selenium concentrations in eggs, because it is the selenium in the egg that actually harms the embryo. Livers of female mallards contain less selenium than livers of males because the egg is a route of excretion for females. The range of concern for selenium concentrations in liver tissue in birds is from 9.9 to 20 µg/g dry weight (table 15). Heinz (1996) suggested a hepatic threshold for reproductive impairment for laying females of 9.9 µg/g dry weight (converted from wet weight using 70 percent moisture), with a somewhat higher concentration range (12 to 18) for non-breeding mallards. Skorupa (1998b) suggested a 30 µg/g dry weight hepatic threshold for juvenile and adult toxicity.

Loss rates of selenium are another important consideration for migratory waterfowl or fish. Surf scoter, greater and lesser scaup, and white sturgeon may experience high selenium exposures during their residence time in the Bay-Delta, but selenium exposures 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 guidelines for producing adverse effects (fig. 17 and table 15). From 1986 to 1990, individual and mean annual average selenium concentrations in liver of surf scoter far exceed guidelines during their residence in Bay-Delta (table 15). Concentrations in liver of surf scoter in the North Bay are in the range of selenium concentrations in livers of ducks, coots, grebes, and stilts sampled at Kesterson Reservoir in 1983–84 (table 15). Hoffman and others (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/g dry weight in greater scaup and 119 µg/g dry weight in surf scoter. Mercury was also measured in this study as it has been suggested that mercury contamination at selenium contaminated sites can be a confounding factor in interpreting tissue concentrations. Surf scoter populations also are rapidly declining in North America and they remain one of the least understood of the migratory waterfowl species (Henny and others, 1995). Selenium concentrations seem to rise extraordinarily in scoter in response to selenium exposures. Henny and others (1995) have suggested that caution should be exercised in linking tissue concentrations to effects in animals with strong bioaccumulative capabilities. For example, in other ecosystems bottle-nosed dolphins (*Tursiops truncates*), Risso's dolphins (*Grampus griseus*), and cormorants seem to bioaccumulate high concentrations of selenium compared to other species. Mineral granules rich in selenium are common in these species (Nigro and Leonzio, 1996). It could be speculated that some species concentrate selenium 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 selenium exposure and effects of selenium across a range of species. Those species exposed to elevated selenium concentrations as a result of their dietary choices should be of special interest in such studies.

Because of the difficulties associated with studies of migratory fauna, no current data are available to help prove that white sturgeon, surf scoter, or greater and lesser scaup are suffering from selenium toxicity or impaired reproduction in the Bay-Delta. However, data both from 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 selenium on reproduction, population biology, and life histories of migratory waterfowl and anadromous fish that are important components of the Bay-Delta ecosystem.

Selenium Hazard Rating

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

Lemly (1995, 1996a) 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.

Table 15. Tissue and dietary selenium guidelines for birds, selenium concentrations in ducks, grebes, and stilts from Kesterson National Wildlife Refuge, and selenium concentrations in surf scoter, greater scaup, and lesser scaup from the North Bay (Suisun and San Pablo Bays).

[Focus is on sensitive endpoints and life stages; diet as selenomethionine; and parental exposure. In general, reproductive endpoints are more sensitive than toxicity and mortality. Within reproductive endpoints, hatchability is the more sensitive endpoint in comparison to deformity. Values are in dry weight with percent moisture given, if applicable.]

Diet or avian tissue (µg/g selenium dry weight)	Approach or site	Effects, species, or North Bay birds	Reference(s)
3–7 (diet); 3–8 (egg)	Synthesis	Range of concern; toxicological and reproductive effects a certainty if upper limit exceeded.	Engberg and others, 1998
3–7 (diet); 6–10 (egg)	Synthesis	Reproductive impairment threshold (population-based for diet; individual based for eggs)	USBR and others, 2004; Presser and others, 2004
3 (diet); 10 (liver); 7 (egg)	Synthesis	Maximum allowable concentrations (protective of reproduction)	Lemly, 2002a
2–4 (diet); 20–30 (liver); 6–15 (egg)	Synthesis	Diagnostic residue for reproductive impairment (deformity or mortality of embryos)	Lemly, 1998b
3.3 (diet based on 10% moisture); 9.9 (liver based on 70% moisture); 13.5 (egg based on 78% moisture)	Synthesis	Thresholds for reproductive impairment; liver of egg-laying mallard (*Anas platyrhynchos*) female associated with reproductive impairment	Heinz and others, 1989; Heinz, 1996
12– 18 (liver based on 70% moisture)	Synthesis	Threshold for reproductive impairment for non-breeding mallards	Heinz and others, 1989; Heinz, 1996
4.87/3.56–5.74 (diet); 12.5/6.4–16.5 (egg)	Lab and synthesis	Hatchability in mallards (10% effect level/ 95% confidence boundaries)	Ohlendorf, 2003
3.85–7.7 (diet based on 10% moisture)	Lab	Reduced hatching success in mallards (33% at 7.7 µg/g); reduced growth and weight in hatchlings	Stanley and others, 1996
7.7 (diet based on 10% moisture)	Lab	Reduction in number of surviving mallard ducklings produced per female	Stanley and others, 1996
8.8 (diet based on 10% moisture)	Lab	Reduction (17%) in survival of mallard ducklings; mean decrease (43%) in number of 6-day-old ducklings	Heinz and others, 1989
6 (diet)	Lab	Adverse effect on body condition of male American kestrels (*Falco sparverius*)	Yamamoto and Santolo, 2000
7.7–8.8 (diet based on 10% moisture)	Synthesis	Dietary threshold of teratogenic effects in mallards; above upper threshold, rate of deformity rises sharply	Stanley and others, 1996
7.7–8.8 (diet based on 10% moisture)	Synthesis	Dietary threshold of mallard duckling mortality (parental exposure)	Stanley and others, 1996
6 (egg)	Synthesis of field data	Threshold (3% effect level) of hatchability in sensitive species (stilts, *Himantopus mexicanus*)	Skorupa, 1998a, b; Skorupa, 1999
8.2 (egg based on 73% moisture)	Field	16% depression in egg viability of spotted sandpiper (*Actitus macularia*)	Harding and others, 2005
5.1 (egg based on 78.4% moisture)	Field	15% depression in egg viability of American dipper (*Cinclus mexicanus*)	Harding and others, 2005
9.0 (mallard egg); 14.5 (stilt egg)	Synthesis	Impaired clutch viability (8.2% effects level for mallard; 11.8% effect level for stilt)	Lam and others, 2005
30 (liver)	Field	Approximate threshold for juvenile/adult toxicity	Skorupa, 1998b
2–180 (egg) 3–360 (liver)	Kesterson Reservoir 1983–1984	Massive deformities and toxicity in aquatic birds	Ohlendorf and others, 1986a; b; Presser and Ohlendorf, 1987; Skorupa, 1998a

Table 15. Tissue and dietary selenium guidelines for birds, selenium concentrations in ducks, grebes, and stilts from Kesterson National Wildlife Refuge, and selenium concentrations in surf scoter, greater scaup, and lesser scaup from the North Bay (Suisun and San Pablo Bays)—Continued.

Diet or avian tissue (µg/g selenium dry weight)	Approach	Effects, species, or North Bay birds	Reference(s)
Avg/range (liver n=71; grand avg=145)	Suisun Bay	surf scoter (*Melanitta perspicillata*), greater scaup (*Aythya marilla*), and lesser scaup (*Aythya affinis*)	White and others, 1987; 1988; 1989; Urquhart and Regalado, 1991
80/37–113 (liver)	(1986)		
84/13–167 (liver)	(1987)		
193/134–244 (liver)	(1988)		
240/137–368 (liver)	(1989)		
127/78–190 (liver)	(1990)		
20.9/3.6–58.6 (flesh n=81)			
Avg/range (liver n=62; grand avg=123)	San Pablo Bay	surf scoter	White and others, 1987; 1988; 1989; Urquhart and Regalado, 1991
74/ 4–148 (liver)	(1986)		
113/65–196 (liver)	(1987)		
135/62–176 (liver)	(1988)		
162/81–217 (liver)	(1989)		
130/84–192 (liver)	(1990)		
20.5/4.5–50 (flesh n=64)			
Avg/range (liver n=39; grand avg=41)	Suisun Bay	greater and lesser scaup	White and others, 1987; 1988; 1989
–/14–86 (liver)	(1986)		
–/8–48 (liver)	(1987)		
85/35–114 (liver)	(1988)		
12.8/2.6–34.6 (flesh n=38)			
Avg/range (liver n=31; grand avg=32)	San Pablo Bay	greater and lesser scaup	White and others, 1987; 1988; 1989
–/12–23 (liver)	(1986)		
–/11–47 (liver)	(1987)		
46/26–87 (liver)	(1988)		
12.9/2.5–35.9 (flesh n=38)			
67 (geometric mean, liver)	Suisun Bay	greater scaup	Hoffman and others, 1998
119 (geometric mean, liver)	(1989)	surf scoter	
41 (geometric mean, liver)		ruddy duck (*Oxyura jamaicensis*)	

- **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 selenium are slightly elevated as compared to uncontaminated reference sites.

- **No hazard:** Selenium concentrations are not elevated in any ecosystem component compared to reference sites.

A scoring method was developed in which points were assigned to define selenium hazard in specific systems: no hazard = 5; minimal hazard = 6 to 8; low hazard = 9 to 11; moderate hazard = 12 to 15; high hazard = 16 to 25 (Lemly, 1995, 1996a). The scores represented summation for the lines of evidence (sampling 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 component (or habitat route), alone, can cause toxicity.

Defined here are four levels of certainty associated with a 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 is available.

- Low certainty results if the hazard evaluation is based on one line of evidence.

Table 16 shows selenium concentrations and the results of hazard analysis from several ecosystems (Lemly, 1985, 1995, 1996a, 1997c; Kroll and Doroshov, 1991) compared to conditions in the Bay-Delta using data collected from 1986 to 1996. These hazard ratings from different ecosystems illustrate the diversity of conditions that can occur in ecosystems receiving selenium discharges. Most notably, high dissolved selenium concentrations in some rivers (such as the LaPlata, Mancos, Animas Rivers in Colorado, New Mexico, and Utah,

Table 16. Selenium hazard ratings for various U.S. sites and for the Bay-Delta.

[Selenium concentrations for each media (water, sediment, invertebrates, fish eggs, and bird eggs) are stated within each cell (µg/L for water and µg/g dry weight for solids). Hazard ratings for each set of concentrations are stated within each cell (as defined by Lemly, 1995 and 1996b). The individual scores and total score are compared to listed evaluation criteria to determine a hazard rating (high, moderate, low, minimal, or none identified) (Lemly, 1995). For the Bay-Delta, bird egg concentrations are converted from bird liver concentrations. Data sources are Lemly, 1995; 1996a, b; 1997a, b, c for western U.S. sites and this report.]

Site or hazard rating	Water (µg/L)/ Hazard	Sediment (µg/g)/ Hazard	Invertebrates (µg/g)/ Hazard	Fish Eggs (µg/g)/ Hazard	Bird Eggs (µg/g)/ Hazard	Score/ Hazard
Ouray Refuge (Leota), Utah	<1–3/low	0.7–1/none	1–3/minimal	2–4/minimal	2–7/low	11/Low
Ouray Refuge (Ponds), Utah	9–93/high	7–41/high	12–72/high	75–120/high	12–120/high	25/high
Ouray Refuge (Sheppard), Utah	3–4/moderate	0.6–3/low	3–33/high	8–27/high	1–17/moderate	21/high
Belews Lake North Carolina (pre-1986)	5–20/high	4–12/high	15–57/high	40–159/high	–	20/high
Belews Lake, North Carolina (1996)	<1/none	1–4/moderate	2–5/moderate	5–20/moderate	2–5/minimal	15/moderate
Animas River, Colorado and New Mexico	1–20/high	0.1–2.3/low	1.8–2.9/minimal	3–16/moderate	–	14/moderate
La Plata River, Colorado and New Mexico	1–12/high	0.1–0.95/none	1.1–2.2/minimal	2.6–39.6/high	–	13/moderate
Mancos River, Colorado and New Mexico	2–29/high	0.2–0.8/none	1.8–11/high	5.6–46/high	–	16/high
Ridges Basin Reservoir, Colorado/New Mexico	1–10/ high	1–8/high	5–75/high	5–100/high	5–100/high	25/high
Southern Ute Reservoir, Colorado/New Mexico	1–6/high	1–5/high	5–50/high	5–80/high	5–80/high	25/high
Bay-Delta, Suisun Bay, 1990–1996	<1/none	0.5–2 (8)/low to moderate	4–20/high	3– 29[a]/high	moderate to high	17/high
None	<1	<1	<2	<3	<3	5
Minimal	1–2	1–2	2–3	3–5	3–5	6–8
Low	2–3	2–3	3–4	5–10	5–12	9–11
Moderate	3–5	3–4	4–5	10–20	12–20	12–15
High	>5	>4	>5	>20	>20	16–25

[a] Kroll and Doroshov (1991).

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, selenium cycling, selenium 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 selenium hazard. In all the reservoirs and pond environments surveyed by Lemly (1995, 1996a, b, 1997a, b, c), elevated dissolved selenium concentrations are accompanied by selenium 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 a high hazard. As residence times increased, the potential increased for selenium to be bioaccumulated, to be deposited in and recycled from sediment, and to adversely affect fish and birds Lemly (1997c). For hazard evaluations, Lemly (1995, 1996a) suggested that sampled nesting birds should be those feeding locally, and that coots, grebes and dabbling ducks were good choices. Suggested choices of fish for hazard evaluation included minnows, sunfish (centrarchids), suckers, catfish, and trout. For the Bay-Delta, however, these species are not the most sensitive because their exposure to selenium 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 times subjected to selenium contamination. A ranking of Suisun Bay under the conditions of 1986–96 is possible using the protocol of Lemly. The results of the aquatic hazard assessment and a hazard rating for the Bay-Delta (table 16) are:

Total score = 17

Hazard rating = 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). Furthermore, toxicity threshold/extinction information, in general, can be related to the selenium 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. (CALFED Bay-Delta Program 1999b, c, and d; and for example, Lucas and Stewart, 2005).

Scenarios and Forecasts

A major goal of this report is to present a systematic approach, the Bay-Delta selenium model (fig. 2), for forecasting the effects of selenium on predators. Several feasible future conditions (scenarios) of selenium loading are used to develop forecasts. The choices of conditions are not nearly as important as the process of evaluating those choices. However, the forecasts that result from chosen scenarios provide guidance to help narrow the range of possible management alternatives.

The approach presented here can be used with any set of explicitly stated conditions, including assumed load scenarios. From each set of assumed conditions, progressive forecasts show:

- loads, volumes, and waterborne concentrations;
- speciation and transformation to particulate material;
- bioaccumulation in generic bivalves (prey); and
- tissue concentrations of predators.

Scenarios of Composite Loads and Volumes to the Bay-Delta

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

[composite freshwater endmember concentration] = [composite source load] ÷ [composite source volume]

Using volumes and source concentrations, composite freshwater endmember selenium concentrations are calculated here for a hypothetical location in the North Bay at the head of the estuary where all sources combine (all loads contribute to a freshwater endmember near the site of input) with instantaneous mixing. A second calculation gives selenium concentrations at Carquinez Strait, a point midway in the North Bay at a salinity of 17.5 psu, (practical salinity units).

Four major sources make up a composite freshwater endmember load: agricultural drainage from direct discharge to the Bay-Delta, effluents from the North Bay refineries, San Joaquin River inflows, and Sacramento River inflows. The composite input volume in the Bay-Delta is most affected by inflows from the Sacramento River and San Joaquin River (figs. 8 and 9). Each of the loads and volumes is constrained here to a given set of conditions to construct feasible scenarios for selenium loads to the Bay-Delta.

Forecasts from the model are presented here by season, where a season is defined as six months of predominantly high river inflows (high flow season, December through May) or six months of predominantly low river inflows (low flow season, June through November). Seasonal presentation (high and low flow seasons) is the least complicated approach to account for riverine influences which are very different in different seasons. Flows also are 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 are additonally determined from monthly loads.

Riverine influences also depend on water-year type. In combination with flow seasons, forecasts also are presented here based on climatic regime. Two regimes are illustrated: a critically dry year and a wet year.

A wide range of agricultural selenium input loads are possible, depending on which management strategies are chosen, as described earlier (also see appendices A and B). Several factors influence agricultural loads of selenium discharged directly to Bay-Delta:

- choice of drainage conveyance, either the San Joaquin River or a San Luis Drain extension;
- demand by agriculture for drainage or a selenium load *targeted* by considering environmental safeguards;
- hydraulic discharge in the San Joaquin River or a San Luis Drain extension;
- selenium concentration in the San Joaquin River or a San Luis Drain extension; and
- proportion of the conveyance discharge that reaches the Bay-Delta.

Potential ranges of annual loads were derived earlier (tables 6 and 7) assuming selenium discharge is continuous. Load scenarios are presented here as discharged load per six months (one-half the annual load under a constant rate of loading). Forecasts are constrained to selected scenarios within the three general ranges of San Joaquin Valley loads described earlier (tables 8 and 9).

1. ***Targeted* loads conveyed by the San Joaquin River (3,400 or 3,590 lbs selenium discharged in six months).** The values used here for *targeted loads* are toward the maximum projected by the TMDL/TMML process (6,547 lbs per year or 3,274 lbs in six months). This load is assumed delivered through the San Joaquin River with full conveyance to the Bay-Delta (no recycling of the San Joaquin River). A San Joaquin River inflow of 0.5 million acre-ft is assumed during the low flow season of both wet and critically dry years. During the high flow season of a wet year, 1.1 million acre-ft is assumed allowed to enter the Bay-Delta.

2. **San Joaquin River used, in effect, as a drain (range of 381 to 15,300 lbs in six months).** If the TMDL/TMML process resulted in management of a constant concentration of selenium in the San Joaquin River year-around, a different load would result than if management is based on load targets. The selenium load delivered to the Bay also would depend on 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 (percentage of San Joaquin River that reaches the Bay-Delta) is necessary, but it should be recognized as hypothetical. Effects of selenium on the San Joaquin River ecosystem are not included in this analysis. Examples of selenium loads that could be transported through the San Joaquin River are given below (also see examples in table 9).

    a. **Load managed at the USEPA selenium criterion of 5 µg/L in a wet year.** A constant selenium concentration of 5.0 µg/L is maintained in the San Joaquin River, with an annual river discharge at Vernalis of 3 million acre-ft. If it is assumed that 75 percent of flow and load reaches the Bay-Delta, then the annual selenium load would be 30,600 lbs (15,300 lbs selenium in six months).

    b. **Load managed at the USFWS recommended selenium criterion of 2 µg/L in a wet year.** In this case, an annual load of 12,240 lbs of selenium is released to the Bay-Delta if a constant selenium concentration of 2.0 µg/L is maintained in the San Joaquin River; annual flow is 3 million acre-ft; and 75 percent of it passes through the Delta (6,120 lbs in six months).

    c. **Dry years.** If annual discharge from the San Joaquin River is 1.1 million acre-ft and 25 percent reaches the Bay-Delta, as might be expected in below normal precipitation, then the annual selenium load would be 9,262 lbs from the San Joaquin River at a 5 µg/L selenium criterion; and 3,705 lbs at a 2 µg/L selenium criterion (1,852 or 4,631 lbs selenium in six months).

    d. **Restored ecosystem.** A constant selenium concentration of 0.5 µg/L is maintained in the San Joaquin River, with 75 percent of the annual San Joaquin River flow and load delivered to the Bay-Delta during the high flow season; and 25 percent allowed to enter in the low flow season. A concentration of 0.5 µg/L is lower than both the USEPA criterion (5 µg/L) and the USFWS recommended criterion (2 µg/L). In this case, an annual load of 4,080 lbs (3,060 lbs during the high flow season; 1,020 lbs during the low flow season) is conveyed by the San Joaquin River assuming an annual flow of 3 million acre-ft in a wet year. In a dry year, an annual load of 1,496 lbs (1,115 lbs during the high flow season; 381 lbs during the low flow season) is conveyed by the San Joaquin River assuming an annual flow of 1.1 million acre-ft. This type of forecast typifies a scenario that considers restoration of the San Joaquin River during proposed increases in flow of the river to aid fish passage.

3. **Demand-driven loads with management of drainage quantity and quality in an extension of the San Luis Drain.** Assumptions used here are (a) demand for drainage is met by construction of a San Luis Drain extension which discharges directly to the Bay-Delta; (b) drainage discharge is either 0.05 million acre-ft each six months (half design flow capacity of existing San Luis Drain, 150 ft^3/s) or 0.11 million acre-ft each six months (full design flow capacity of San Luis Drain, 300 ft^3/s); and (c) selenium concentrations will vary with the success of treatment. Specific forecasts are:

    a. **Demand-driven loads with priority given to management of quality and quantity (6,800 or 18,700 lbs selenium discharged in six months).** Two load scenarios are calculated for this condition. One scenario is calculated assuming a condition of 150 ft^3/s in the San Luis Drain (0.05 million acre-ft of drainage or half capacity) with a selenium concentration of 50 µg/L. Under this condition, 6,800 lbs selenium is discharged in six months. In a second scenario, 62.5 µg/L drainage is assumed discharged at full capacity (0.11 million acre-ft); the load discharged is 18,700 lbs selenium per six months. These two loads bracket the lowest end of the range of cumulative potential loads from the different subareas (or combinations of subareas) of the San Joaquin Valley (tables 5 through 7).

    b. **Demand-driven loads with low priority given to management of quality and quantity (44,880 and 89,760 lbs selenium in six months).** Two load scenarios are calculated 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 assumes a 150 µg/L selenium concentration in a San Luis Drain extension with the drain running at full capacity (0.11 million acre-ft in six months) (44,880 lbs selenium discharged in six months). The second case assumes 300 µg/L and 0.11 million acre-ft of discharge in six months (89,760 lbs selenium discharged in six months), assuming little regional management (as described earlier). These two loads bracket the high end of the range of potential loads from a valley-wide system draining most potential problem lands, with minimal management (tables 6 through 8).

Calculation of total selenium loads to the Bay-Delta and resulting selenium concentrations consider climate, oil refinery loads, San Joaquin River recycling, and Sacramento River condition as follows:

1. As noted previously, the magnitude and fate of selenium loads are highly dependent on climatic regime. Climate regimes are derived from existing data:
    a. *Critically dry year.* Eight critically dry years in the Bay-Delta watershed occurred between 1978 and 1998, so this is an important factor to consider. Data for this condition are from 1994.
    b. *Wet year.* Data from 1997, a wet year as designated by the Department of Water Resources, are used.
2. In all scenarios, oil refineries are assumed to meet the 1998 permit requirements of approximately 1,360 lbs selenium per year or 680 lbs per six months. Oil refinery loads measured in 1999 totaled 1,115 lbs selenium (table 10), similar to the assumed amount.
3. In demand-driven load scenarios during critically dry years, selenium loads from the San Joaquin River are assumed to be low. These scenarios implicitly assume that use of a San Luis Drain extension could relieve the pressure for discharge of drainage to the San Joaquin River. These scenarios also assume continued substantial recycling of the San Joaquin River, so only 500 to 1,000 acre-ft of San Joaquin River flow reaches the Bay-Delta in critically dry years during high or low flow seasons. If selenium concentrations of 1 or 2 µg/L are assumed to be maintained in the river, then the San Joaquin River delivers 3 to 5 lbs selenium in six months.
4. During wet years in periods of high flow, less recycling of the San Joaquin River occurs, with substantially more San Joaquin River throughput to the Bay-Delta. To accurately reflect this condition in demand-driven load forecasts, 2 million acre-ft of San Joaquin River flow is assumed to reach the Bay-Delta. A concentration of 1 µg/L is assigned for this inflow (5,440 lbs selenium in six months).
5. Loads from the Sacramento River are calculated using measured hydraulic discharge and assuming a selenium concentration of 0.04 µg/L.

A summary of feasible future conditions and selenium loads for the Bay-Delta is shown in table 17. Specific load scenarios employed in modeling bioaccumulation and predicting effects on predators are highlighted in summary tables that follow (tables 18 through 22). The compilation is not exhaustive in its coverage of all conditions; but the choices bracket the wide range of loads possible in the future from western San Joaquin Valley acreage that is in need of drainage (tables 8 and 9, and appendix B).

Comparison of forecasted selenium concentrations to observed conditions prior to refinery cleanup

To initially test the validity of the approach, an average composite freshwater endmember selenium concentration is calculated for conditions resembling those that were documented in the North Bay prior to refinery cleanup (table 18). Forecasts are for the high flow season during a wet year; and for the low flow season during both a wet and critically dry year, similar to conditions selected for projections of future conditions (see tables 19 through 21). Sacramento River inflow for six months of high flow was taken from 1997 data (17 million acre-ft). Sacramento River inflows during six months of low flow in 1997 and 1994, respectively, provide the two other cases (2.3 and 1.62 million acre-ft). San Joaquin River inflow was 3 million acre-ft for high flow in 1997 and 0.1 million acre-ft in the latter two low-flow cases. Refinery discharges (2,040 lbs in six months) are in the range measured before refinery cleanup (average 1986–92; 2,505 lbs per six months) (table 10) (San Francisco Bay Board, 1992a, b, 1993). No San Luis Drain discharge is included for these forecasts.

The forecasted average composite freshwater endmember concentration of selenium during six months of high flow in a wet year is 0.22 µg/L (table 18). The forecasted concentration is comparable to a selenium concentration of 0.16 µg/L determined after high flows in April 1986 (Cutter, 1989). The contrasting influences of the San Joaquin River and the Sacramento River are interesting to note in this example. Selenium concentrations in the San Joaquin River are much higher than concentrations in the Sacramento River (1 µg/L and 0.04 µg/L, respectively). The load of selenium from the San Joaquin River also is substantial compared with the load from the Sacramento River (8,160 lbs compared with 1,850 lbs per six months, respectively). Concentrations of selenium are as low as 0.22 µg/L at the head of the estuary because of dilution by the high volume of lower-selenium water from the Sacramento River. A selenium concentration of 0.11 µg/L is projected at the selected seaward location of Carquinez Strait.

The concentration of selenium at 17.5 psu (approximate location of Carquinez Strait) during the six months of low flow in a wet year is projected as 0.20 µg/L; in a critically dry year it is 0.27 µg/L (table 18). The composite freshwater endmember concentrations for these two forecasts are 0.39 and 0.53 µg/L, respectively. Selenium concentrations are highest during periods of low flows, because dilution from the Sacramento River is reduced in years of low rainfall. The forecasted concentrations are remarkably close to the range of values found within the estuary by Cutter (1989) (0.15 to 0.44 µg/L selenium). The correspondence of these calculations with observed data confirms that the basic foundation of the model and forecasts are reasonable.

Table 17. Selenium loads employed in forecasts of selenium effects.

[Loads are calculated per six month. Annual loads would be two times higher if selenium discharge is continuous (at a constant rate). Agricultural inputs fall into three groups depending on management strategy: supply-driven management (3,000 to 8,000 lbs selenium per year); demand-driven load with management of land and/or drainage quality (15,000 to 45,000 lbs selenium per year); and demand-driven load with minimum management (45,000 to 128,000 lbs selenium per year).]

Inputs to Bay-Delta	Wet year/high flow (lbs selenium per six months)	Wet year/low flow (lbs selenium per six months)	Critically dry/low flow (lbs selenium per six months)
San Luis Drain extension 50 µg/L, 150 ft^3/s, 0.05 MAF/season	6,800	6,800	6,800
San Luis Drain extension 62.5 µg/L, 300 ft^3/s, 0.11 MAF/season	18,700	18,700	18,700
San Luis Drain extension 150 µg/L, 300 ft^3/s, 0.11 MAF/season	44,880	44,880	44,880
San Luis Drain extension 300 µg/L, 300 ft^3/s, 0.11 MAF/season	89,760	89,760	89,760
San Joaquin River (*targeted* load)	3,400–3,600	3,400–3,600	3,400–3,600
San Joaquin River (maximum recycling)	3–5	3–5	3–5
Oil Refineries	680	680	680
Sacramento River	141	250	1,850

Table 18. Calculation of selenium concentrations for a composite freshwater endmember at the head of the estuary and at Carquinez Strait (a point midway in the North Bay at a salinity of 17.5 practical salinity units) under conditions simulating those prior to refinery cleanup.

[Inputs are from the Sacramento River, San Joaquin River, and oil refineries, with no input from a proposed San Luis Drain extension. Forecasts contrast wet and dry years; and high and low seasons. Table is a representation of a spreadsheet. Carqinez Strait location at 17.5 psu]

Conditions prior to refinery cleanup							
	Volume (million acre-ft)	Volume (billion liters)	Selenium				
			Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (µg/L)
Wet year (1997 data), high flow season (six months, December through May)							
Sacramento River	17	20,961	0.04	838	1,850		
San Joaquin River	3	3,699	1	3,699	8,160		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6	150	925	2,040		
						0.22	0.11
Wet year (1997 data), low flow season (six months, June through November)							
Sacramento River	2.3	2,836	0.04	113	250		
San Joaquin River	0.1	123	1	123	272		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6	150	925	2,040		
						0.39	0.20
Critically dry year (1994 data), low flow season (six months, June through November)							
Sacramento River	1.62	1,998	0.04	80	176		
San Joaquin River	0.1	123	1	123	272		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6	150	925	2,040		
						0.53	0.27

Table 19. Forecasts of selenium concentrations for a composite freshwater endmember at the head of the estuary and at Carquinez Strait (a point midway in the North Bay at a salinity of 17.5 practical salinity units) for a wet year in a high flow season under load scenarios for conveyance of agricultural drainage either through a San Luis Drain extension or the San Joaquin River.

[Inputs from the Sacramento River and oil refineries also are considered. Refinery cleanup is assumed in all scenarios. Scenarios using a San Luis Drain extension for conveyance assume a 2 million acre-ft inflow reaches the Bay-Delta. The scenario using the San Joaquin River for conveyance assumes no San Luis Drain inflow and a 1.1 million acre-ft inflow reaches the Bay-Delta. This table is a representation of a spreadsheet.]

Wet year (1997 data); high flow season (six months, December through May); refinery cleanup

	Volume (million acre-ft)	Volume (billion liters)	Selenium				
			Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (µg/L)
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup							
Sacramento River	17	20,961	0.04	838	1,850		
San Joaquin River	2	2,466	1	2,466	5,440		
San Luis Drain	0.05	62	50	3,083	6,800		
Refineries	0.005	6	50	308	680		
						0.28	0.14
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup							
Sacramento River	17	20,961	0.04	838	1,850		
San Joaquin River	2	2,466	1	2,466	5,440		
San Luis Drain	0.11	136	62.5	8,477	18,700		
Refineries	0.005	6	50	308	680		
						0.51	0.26
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup							
Sacramento River	17	20,961	0.04	838	1,850		
San Joaquin River	2	2,466	1	2,466	5,440		
San Luis Drain	0.11	136	150	20,345	44,800		
Refineries	0.005	6	50	308	680		
						1.02	0.51
Load scenario: San Luis Drain extension at 300 ft^3/s and 300 µg/L for a load of 89,760 lbs per six months; refinery cleanup							
Sacramento River	17	20,961	0.04	838	1,850		
San Joaquin River	2	2,466	1	2,466	5,440		
San Luis Drain	0.11	136	300	40,689	89,760		
Refineries	0.005	6	50	308	680		
						1.88	0.94
Load scenario: *Targeted* San Joaquin River load of 7,180 lbs annually (3,590 lbs per six months); refinery cleanup							
Sacramento River	17	20,961	0.04	838	1,850		
San Joaquin River	1.1	1,356	1.2	1,628	3,590		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6	50	308	680		
						0.12	0.06

Table 20. Forecasts of selenium concentrations for a composite freshwater endmember at the head of the estuary and at Carquinez Strait (a point midway in the North Bay at a salinity of 17.5 practical salinity units) for a wet year in a low flow season under load scenarios for conveyance of agricultural drainage either through a San Luis Drain extension or the San Joaquin River.

[Inputs from the Sacramento River and oil refineries also are considered. Refinery cleanup is assumed in all scenarios. Scenarios using a San Luis Drain extension for conveyance assume little San Joaquin River inflow reaches the Bay-Delta. The scenario using the San Joaquin River for conveyance assumes no San Luis Drain extension inflow and a 0.5 million acre-ft inflow from the San Joaquin River reaches the Bay-Delta. This table is a representation of a spreadsheet.]

Wet year (1997 data); low flow season (six months, June through November); refinery cleanup							
	Volume (million acre-ft)	**Volume (billion liters)**	**Selenium**				
			Concentration (µg/L)	**Load (billion µg)**	**Load (lbs per six months)**	**Freshwater endmember (µg/L)**	**Carquinez Strait (µg/L)**
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup							
Sacramento River	2.3	2,836	0.04	113	250		
San Joaquin River	0.001	1.2	1	1	3		
San Luis Drain	0.05	62	50	3,083	6,800		
Refineries	0.005	6.2	50	308	680		
						1.21	0.60
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup							
Sacramento River	2.3	2,836	0.04	113	250		
San Joaquin River	0.001	1.2	2	2	5		
San Luis Drain	0.11	136	62.5	8,477	18,700		
Refineries	0.005	6.2	50	308	680		
						2.99	1.49
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup							
Sacramento River	2.3	2,836	0.04	113	250		
San Joaquin River	0.001	1.2	2	2	5		
San Luis Drain	0.11	136	150	20,345	44,880		
Refineries	0.005	6.2	50	308	680		
						6.97	3.49
Load scenario: San Luis Drain extension at 300 ft^3/s and 300 µg/L for a load of 89,760 lbs per six months; refinery cleanup							
Sacramento River	2.3	2,836	0.04	113	250		
San Joaquin River	0.001	1.2	2	2	5		
San Luis Drain	0.11	136	300	40,689	89,760		
Refineries	0.005	6.2	50	308	680		
						13.8	6.90
Load scenario: *Targeted* San Joaquin River load of 7,180 lbs annually (3,590 lbs per six months); refinery cleanup							
Sacramento River	2.3	2,836	0.04	113	250		
San Joaquin River	0.5	616	2.5	1,541	3,400		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6.2	50	308	680		
						0.57	0.28

Table 21. Forecasts of selenium concentrations for a composite freshwater endmember at the head of the estuary and at Carquinez Strait (a point midway in the North Bay at a salinity of 17.5 practical salinity units) for a critically dry year in a low flow season under load scenarios for conveyance of agricultural drainage either through a San Luis Drain extension or the San Joaquin River.

[Inputs from the Sacramento River and oil refineries also are considered. Refinery cleanup is assumed in all scenarios. Scenarios using a San Luis Drain extension for conveyance assume little San Joaquin River inflow reaches the Bay-Delta. The scenario using the San Joaquin River for conveyance assumes no San Luis Drain extension inflow and a 0.5 million acre-ft inflow from the San Joaquin River reaches the Bay-Delta. This table is a representation of a spreadsheet.]

Critically dry year (1994 data); low flow season (six months, June through November); refinery cleanup							
	Volume (million acre-ft)	**Volume (billion liters)**	**Selenium**				
			Concentration (µg/L)	**Load (billion µg)**	**Load (lbs per six months)**	**Freshwater endmember (µg/L)**	**Carquinez Strait (µg/L)**
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup							
Sacramento River	1.3	1,603	0.04	64	141		
San Joaquin River	0.0005	0.6	2	1	3		
San Luis Drain	0.05	62	50	3,083	6,800		
Refineries	0.005	6.2	50	308	680		
						2.07	1.03
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup							
Sacramento River	1.3	1,603	0.04	64	141		
San Joaquin River	0.0005	0.6	2	1	3		
San Luis Drain	0.11	136	62.5	8,477	18,700		
Refineries	0.005	6.2	50	308	680		
						5.07	2.54
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup							
Sacramento River	1.3	1,603	0.04	64	141		
San Joaquin River	0.001	1.2	2	2	5		
San Luis Drain	0.11	136	150	20,345	44,880		
Refineries	0.005	6.2	50	308	680		
						11.87	5.93
Load scenario: San Luis Drain extension at 300 ft^3/s and 300 µg/L for a load of 89,760 lbs per six months; refinery cleanup							
Sacramento River	1.3	1,603	0.04	64	141		
San Joaquin River	0.0005	0.6	2	1	3		
San Luis Drain	0.11	136	300	40,689	89,760		
Refineries	0.005	6.2	50	308	680		
						23.53	11.76
Load scenario: *Targeted* San Joaquin River load of 6,800 lbs annually (3,400 lbs per six months); refinery cleanup							
Sacramento River	1.3	1,603	0.04	64	141		
San Joaquin River	0.5	616	2.5	1,541	3,400		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6.2	50	308	680		
						0.86	0.43

Table 22. Forecasts of selenium concentrations for a composite freshwater endmember at the head of the estuary and at Carquinez Strait (a point midway in the North Bay at a salinity of 17.5 practical salinity units) under a restoration scenario that assumes greater San Joaquin River inflows enter the Bay-Delta to aid fish migration and the concentration in the river maintained at 5 µg/L.

[The high flow season is assumed to convey 75% of the San Joaquin River annual flow; and the low flow season conveys 25%. Refinery cleanup and no San Luis Drain extension is assumed in all scenarios. This table is a representation of a spreadsheet.]

Restoration scenarios							
			Selenium				
	Volume (million acre-ft)	Volume (billion liters)	Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (µg/L)
Wet year (1997 data); high flow season; conveys 75% of San Joaquin River inflow (six months, December through May)							
Sacramento River	17	20,961	0.04	838	1,850		
San Joaquin River	2.25	2,774	0.5	1,387	3,060		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6.2	50	308	680		
Total	19.25				5,590	0.11	0.05
Wet year (1997 data); low flow season; conveys 25% of San Joaquin River inflow (six months, June through November)							
Sacramento River	2.3	2,836	0.04	113	250		
San Joaquin River	0.75	925	0.5	462	1,020		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6.2	50	308	680		
Total	3.055				1,950	0.23	0.12
Dry year (1994 data); high flow season; conveys 75% of San Joaquin River inflow (six months, December through May)							
Sacramento River	5	6,165	0.04	247	544		
San Joaquin River	0.82	1,011	0.5	506	1,115		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6.2	50	308	680		
Total	5.825				2,339	0.15	0.07
Dry year (1994 data); high flow season; conveys 25% of San Joaquin River inflow (six months, June through November)							
Sacramento River	1.6	1,973	0.04	79	174		
San Joaquin River	0.28	345	0.5	173	381		
San Luis Drain	0	0	0	0	0		
Refineries	0.005	6.2	50	308	680		
Total	1.885				1,235	0.24	0.12

Forecasts of influence of selenium discharged through a San Luis Drain extension: seasonal waterborne selenium concentrations

Four specific forecasts are constructed to evaluate effects on the Bay-Delta of direct discharge from an extension of the San Luis Drain (tables 19 through 21). Those forecasts are based on feasible loads under three different sets of climate and river inflows conditions (wet year, high flow season; wet year, low flow season; and critically dry year, low flow season) as described earlier.

1. **6,800 lbs selenium discharged in six months if management of drainage quality and quantity are a high priority (half-capacity or 150 ft^3/s of drain water with a selenium concentration of 50 µg/L).** The forecasted six-month average selenium concentrations at the head of the estuary (com-

posite freshwater endmember concentration) during the low flow season range from 1.21 µg/L in a wet year (table 20) to 2.07 µg/L during a critically dry year (table 21). A selenium concentration of 0.28 µg/L (table 19) is forecasted in the high flow season of a wet year. Forecasted selenium concentrations at the selected seaward location of Caquinez Strait are: the low flow season of a wet year, 0.60 µg/L; the low flow season of a critically dry year, 1.03 µg/L; and the high flow season of a wet year 0.14 µg/L (tables 19 through 21).

2. **18,700 lbs selenium discharged in six months if a San Luis Drain extension operates at full capacity (300 ft^3/s), carrying drainwater with a selenium concentration similar to that in the Grassland Bypass Channel Project (reuse of the drain project, 62.5 µg/L).** This forecast is one of the more likely demand-driven loads in the long-term if successful treatment technology is applied to drainage and the amount of *problem land* is that considered by the Drainage Program (table 6). Forecasted selenium concentrations at the head of the estuary are projected to average 2.99 µg/L during the low flow season of a wet year; and 5.07 µg/L during six months of low flow in a critically dry year. Selenium concentrations average 0.51 µg/L at the head of the estuary during six months of high flow in a wet year.

3. **44,880 lbs selenium discharged in six months if drainage contains 150 µg/L selenium and the drain operates at full capacity.** This load would provide for drainage from *problem lands* without investment in management of drainage (such as direct discharge of shallow ground water). Even during high flow, selenium concentrations are projected to exceed 1 µg/L (1.02 µg/L) at the head of the estuary under these conditions. During low flow, six-month average concentrations (6.97 to 11.87 µg/L) always exceed the USEPA criterion of 5 µg/L no matter what the rainfall.

4. **89,760 lbs selenium discharged in six months if the most severely salinized soils supply a drain at full capacity and no treatment technology is available**. This scenario is not highly likely given expected emphasis on source control and treatment. However, if it should occur, extremely high selenium concentrations are found in the estuary under low flow conditions (13.8 to 23.5 µg/L, rounded off) (tables 19 through 21). Average concentration at the head of the estuary (1.88 µg/g) approximately equals the USFWS recommended criterion (2 µg/L), even during the high flow season (table 21).

Forecasts of the influence of selenium discharged through the San Joaquin River: seasonal waterborne selenium concentrations

1. **Regulating load.** This scenario assumes a selenium load limited for regulatory or environmental purposes at 7,000 lbs selenium per year and 3,500 lbs selenium discharged in six months. Conveyance is fully through the San Joaquin River. The projected range of selenium concentrations in the freshwater endmember for the Bay-Delta during the low flow season scenarios is 0.57 to 0.86 µg/L selenium; concentrations range from 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 selenium at the head of the estuary and 0.20 to 0.27 µg/L selenium at Carquinez Strait) (table 18). So, in terms of affecting total selenium concentrations, this *targeted* load of selenium from the San Joaquin Valley would replace the selenium removed by investment in refinery waste treatment. If 3,590 lbs of selenium are discharged during a six-month high flow season of a wet year (table 19), concentrations are twofold lower (0.12 µg/L at the head of the estuary and 0.06 µg/L at Carquinez Strait) than conditions prior to refinery cleanup (0.22 µg/L at the head of the estuary and 0.11 µg/L at Carquinez Strait, table 18).

2. **Regulating concentrations in the San Joaquin River: a restoration forecast.** Environmental restoration is often vaguely defined. A specific *restoration* scenario for the San Joaquin River might place explicit limits on selenium concentrations in the river and emphasize increasing San Joaquin River inflows (less recycling of the San Joaquin River) 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 San Joaquin River contrasts to previous scenarios in which selenium load is managed. In calculating the effect of such *restoration* on selenium concentrations in the Bay-Delta, the concentration assigned in the *restoration* scenario is 0.5 µg/L for the San Joaquin River at Vernalis. It should be noted that this concentration has not been achieved in the recent past (table 5). Further, it is not implied here that the technology is available to achieve this concentration or that it would be easy to achieve by management decree. This is a specific condition done for illustrative purposes. Conditions and selenium loads for this *restoration* scenario (table 22) include:

    - no San Luis Drain discharge;
    - constrain concentrations in the San Joaquin River at Vernalis to 0.5 µg/L;
    - convey 75 percent of the annual San Joaquin River flow and load to the Bay-Delta in the high flow season and 25 percent in the low flow season;
    - assume the San Joaquin River inflow for a wet year is 3 million acre-ft and for a dry year is 1.1 million acre-ft;
    - control industrial discharges to meet the July 1998 mandate of approximately 1,400 lbs selenium per year;
    - vary Sacramento River inputs with river flow as is done now (0.04 µg/L at 19.3 million acre-ft annual inflow in a wet year and 0.04 µg/L at 6.6 million acre-ft annual inflow in a dry year).

Under a *restoration* scenario in the high flow season, composite freshwater endmember selenium concentrations are projected at 0.11 and 0.15 µg/L for a wet year and a dry year, respectively (table 22). In the low flow season, composite freshwater endmember selenium concentrations are projected at 0.23 and 0.24 µg/L, respectively (table 22). These selenium concentrations are 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, and 21 to table 22). Conditions are most improved, compared to before refinery cleanup, during the *bottleneck* period of the low flow season (that is, the defining period for selenium ecological effects) in both wet and dry years. Less increase in concentration occurs in the Bay-Delta during low flow seasons in a *restoration* scenario because selenium inputs decline as flows decline. In high flow seasons, selenium inputs increase, but the increase in dilution due to the higher inflows of the Sacramento River offset the higher loads from the San Joaquin River and concentrations in the Bay-Delta decline.

3. **Regulating selenium concentrations in the San Joaquin River: effect of high flows and consequent high loads as a result of expanded selenium objectives.** The advantage of discharging an increased selenium load during high flows under a concentration management scenario does have some limitations in the low flow season and if selenium concentrations in the San Joaquin River increase. The concentration objective at which the San Joaquin River is held constant by implementation of a management plan is increased in a series of scenarios illustrated in figure 18. If the selenium concentration in the San Joaquin River 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/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 selenium during a dry year in the low flow season. In this case (above the crossover point, fig. 18), the estuary during 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 a higher selenium load discharged during a wet year is not offset as much by increased flows as occurs seasonally.

Forecasts of the influence of selenium discharges: monthly waterborne selenium concentrations

The six-month scenarios described above represent average seasonal selenium concentrations (low flow season compared to 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, selenium concentrations are forecast that result from monthly loads. The forecasts are based on wet year flows (1997). The results of the monthly forecasts are presented graphically in figures 19 and 20 and supplemental data are given in appendix F, tables F1 and F2. Conditions used in the forecasts and results of the forecasts are:

Operation of a San Luis Drain extension at full capacity (0.22 million acre-ft/yr) conveying drainage at quality levels typical of the present reuse of the drain by Grassland subarea (62.5 µg/L). The annual load of selenium is 36,720 lbs (or about 18,700 × 2 = 37,400 lbs, table 17). Although monthly drain discharge is constant (3,060 lbs per month) in this scenario, forecasted selenium concentrations at the head of the estuary increase progressively from 0.24 µg/L in January to 4.5 µg/L in October (fig. 19). 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 selenium concentrations as long as a constant load is released from the drain throughout the year (fig. 19). The vulnerability of the estuary to adverse effects is generally greatest during the season 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 (figs. 8 and 9). Figure 19 expresses this scenario as a function of both load and composite freshwater endmember selenium concentration. Figure 20 shows the composite freshwater endmember selenium concentration at the head of the estuary and the selenium concentration at Carquinez Strait for comparison.

Management of the San Joaquin River at 2 µg/L selenium with full conveyance to the Bay-Delta during a wet year (6.06 million acre-ft/yr). It is also instructive to evaluate

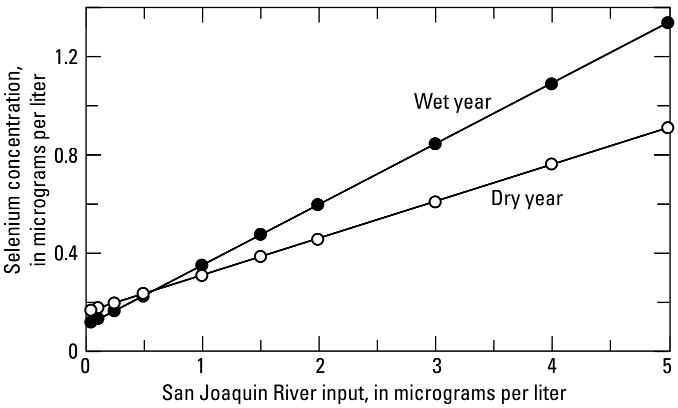

Figure 18. Forecasts of composite freshwater endmember selenium concentrations for a series of concentration management scenarios for the San Joaquin River in low flow seasons of both wet and dry years.

the variation in monthly concentrations that might develop at the head of the estuary as a result of managing a constant San Joaquin River selenium concentration. The annual load of selenium discharged to the Bay-Delta from the San Joaquin River in this forecast is similar to that discharged by a San Luis Drain extension in the above scenario (32,936 lbs compared with 36,720 lbs for the San Luis Drain scenario, table 17). The highest loads (about 10,400 lbs each month) are discharged in January and February. The highest selenium 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 (fig. 20). The latter period of elevated concentration coincides with that under constant discharge from the San Luis Drain (fig. 20). Selenium concentrations in the Bay-Delta are much lower from April through December if the San Joaquin River is the conveyance rather than if a San Luis Drain extension is the conveyance. This disparity in load is because monthly loads from the San Joaquin River 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 selenium concentration illustrates an important problem with releasing selenium through an artificial conveyance facility. Additional limitations also exist when large loads are released during high flows (see fig. 18 and later discussion).

Management of the San Joaquin River at 1 µg/L selenium with full conveyance to the Bay-Delta during a wet year. The annual load calculated for this condition is 16,468 lbs in a high flow year. The monthly trends are the same as those under the 2 µg/L selenium scenario, but the amplitude of the fall peak is reduced (fig. 19). The highest concentrations in the landward reach of the estuary are 0.60 and 0.68 µg/L in September and October (appendix F, table F2), respectively (about 1.5 times the maximum observed before refinery cleanup, table 18). Forecasted concentrations near Carquinez Strait in October (fig. 20) are about equal to the highest concentrations (0.30 to 0.34 µg/L) observed prior to refinery cleanup based on a seasonal analysis (table 18), although speciation would probably be different (see later discussion).

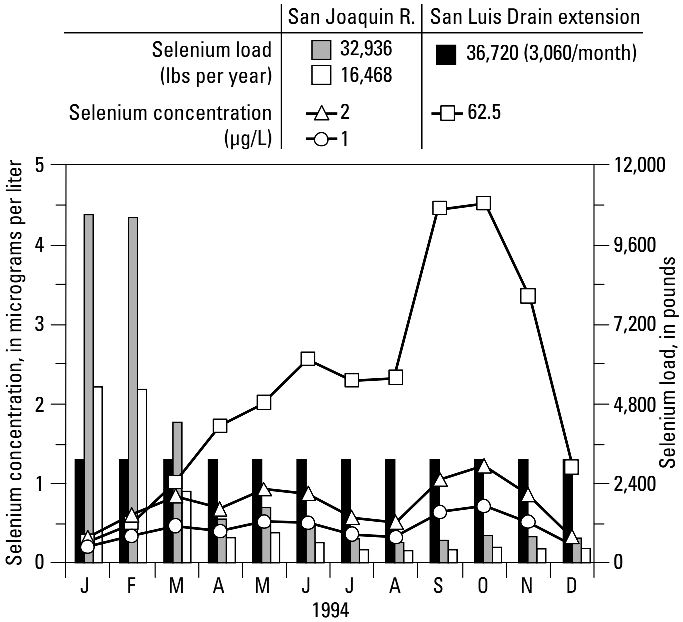

Figure 19. Forecasts of monthly composite freshwater endmember selenium concentrations under three discharge scenarios (San Joaquin River at 1 and 2 µg/L selenium; San Luis Drain extension at 62.5 µg/L selenium) contrasted to input concentrations and loads.

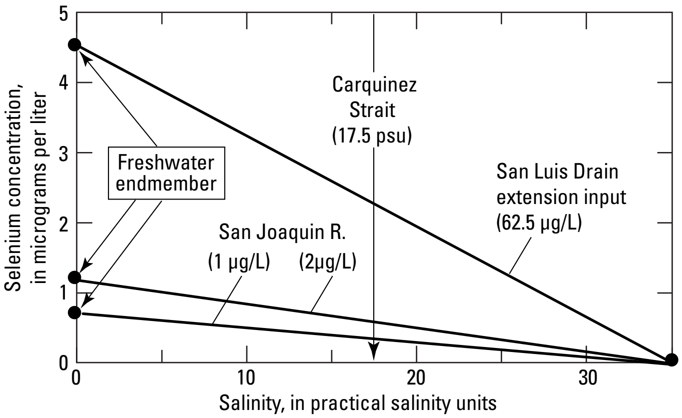

Figure 20. Forecasts of selenium concentrations for a composite freshwater endmember at the head of the estuary and at Carquinez Strait (a point midway in the North Bay at a salinity of 17.5 practical salinity units) under three load scenarios (San Joaquin River at 1 and 2 µg/L selenium; San Luis Drain extension at 62.5 µg/L selenium) based on dilution of selenium through the estuary as function of salinity in October, 1997.

Summary of forecasts

Forecasts of selenium concentrations in a composite freshwater endmember entering the Bay-Delta as a result of loads discharged through a San Luis Drain extension and a *targeted* load discharged through the San Joaquin River overall show that the most vulnerable years are critically dry years (table 23; figs. 21 and 22). The low flow season is the critical period of each year for the Bay-Delta. However, if selenium concentration in the San Joaquin River is regulated under a constant concentration management plan and San Joaquin River inflows are increased, wet years are more vulnerable than dry years, but only during the low flow season (fig. 18).

A generalized graphical tool presented in figure 22 can be used to forecast waterborne selenium concentrations resulting from a wide range of six-month hydraulic discharges (emphasizing lower flow seasons) and selenium loads. Each line represents a selenium concentration resulting from a different combinations of variables. From figure 22, the composite

Table 23. Summary of forecasts of selenium concentrations for a composite freshwater endmember at the head of the estuary and at Carquinez Strait (at 17.5 practical salinity units) under projected selenium load scenarios.

Scenario	Water-column selenium concentrations (µg/L)						
	Past	**San Luis Drain extension**				**San Joaquin River**	
	Prior to refinery cleanup	**Half capacity at 50 µg/L**	**Full capacity at 62.5 µg/L**	**Full capacity at 150 µg/L**	**Full capacity at 300 µg/L**	***Targeted* Load**	**Restoration 0.5 µg/L**
			Wet year/high flow				
Load (lbs per six months)	–	6,800	18,700	44,880	89,760	3,590	3,060
Endmember concentration (µg/L)	0.22	0.28	0.51	1.02	1.88	0.12	0.11
Carquinez Strait concentration (µg/L)	0.11	0.14	0.26	0.51	0.94	0.06	0.05
			Wet year/low flow				
Load (lbs per six months)	–	6,800	18,700	44,880	89,760	3,400	1,020
Endmember concentration (µg/L)	0.39	1.21	2.99	6.97	13.8	0.57	0.23
Carquinez Strait concentration (µg/L)	0.20	0.60	1.49	3.49	6.9	0.28	0.12
			Critically dry year/low flow				
Load (lbs per six months)	–	6,800	18,700	44,880	89,760	3,400	381
Endmember Concentration (µg/L)	0.53	2.07	5.07	11.9	23.5	0.86	0.24
Carquinez Strait concentration (µg/L)	0.27	1.03	2.54	5.93	11.8	0.43	0.12

freshwater endmember concentration of selenium (that concentration at the head of the estuary) can be estimated from any combination of climate (as indicated by differing total river inflows) and selenium load. The strong dependence of selenium contamination on weather and water demand (which, together, determine discharge to the estuary) is evident. Figure 22 illustrates the extreme vulnerability of the estuary to selenium inputs during low flow seasons (cumulative discharges of 1 to 2 million acre-ft over six months). For example, for total loads of approximately 7,700 lbs, 20,000 lbs, and 46,000 lbs selenium at defined cumulative volumes of 1.3 and 2.3 million acre-ft during low flow seasons, the range of estuary selenium concentrations is from 1.2 to 12 µg/L.

Under the range of illustrated load scenarios, selenium concentrations in the Bay-Delta increase in all scenarios that include a San Luis Drain extension, and especially as the flow capacity of the San Luis Drain is achieved and/or if concentrations of selenium increase in the discharge (table 23 and fig. 21). A minimum estimate of loads from a San Luis Drain extension is 6,800 lbs per six months (or 13,600 lbs annually). This scenario can only be achieved if the drain is managed at a flow of 150 ft^3/s and the most optimistic treatment technologies are invoked. Even under this load scenario, composite freshwater endmember selenium concentrations would increase two to fourfold over concentrations typical prior to refinery cleanup (also see table 18). Freshwater endmember selenium concentrations in the driest of years are projected to exceed 2 µg/L toward the head of the estuary.

If a San Luis Drain 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 a San Luis Drain extension may approach the level of 18,700 lbs per six months (37,400 lbs per year). Under this load scenario, average selenium concentrations in the Bay-Delta at the head of the estuary for the six-month low flow season of a wet or critically dry year are forecast to exceed the USFWS recommended criterion of 2 µg/L through all of Suisun Bay (table 22 and fig. 21). This exceedance also occurs at Carquinez Strait during the low flow period of critically 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 (that is, selenium concentrations could increase). If, on average, drainage quality becomes similar to that of subsurface drainage (equal to or greater than 150 µg/L selenium) rather than blended drainage in the western San Joaquin Valley, and that is combined with

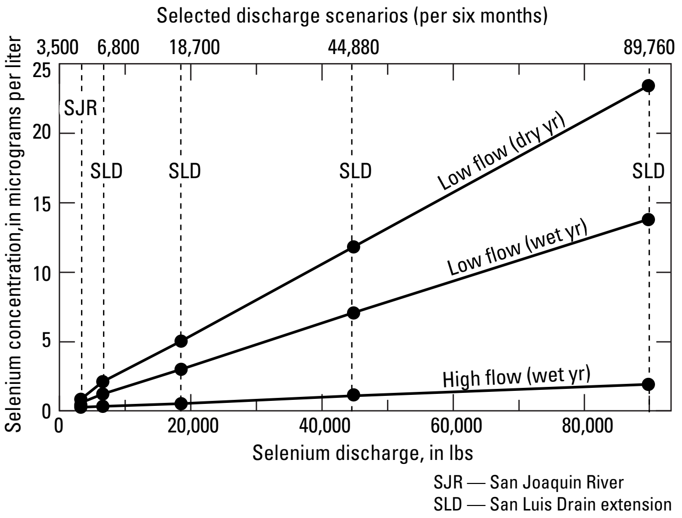

Figure 21. Forecasts of seasonal composite freshwater endmember concentrations under five discharge scenarios (San Luis Drain extension at 6,800, 18,700, 44,880, and 89,760 lbs selenium per six months; San Joaquin River at 3,500 lbs selenium per six months) for the high flow season of a wet year and the low flow seasons of wet and dry years.

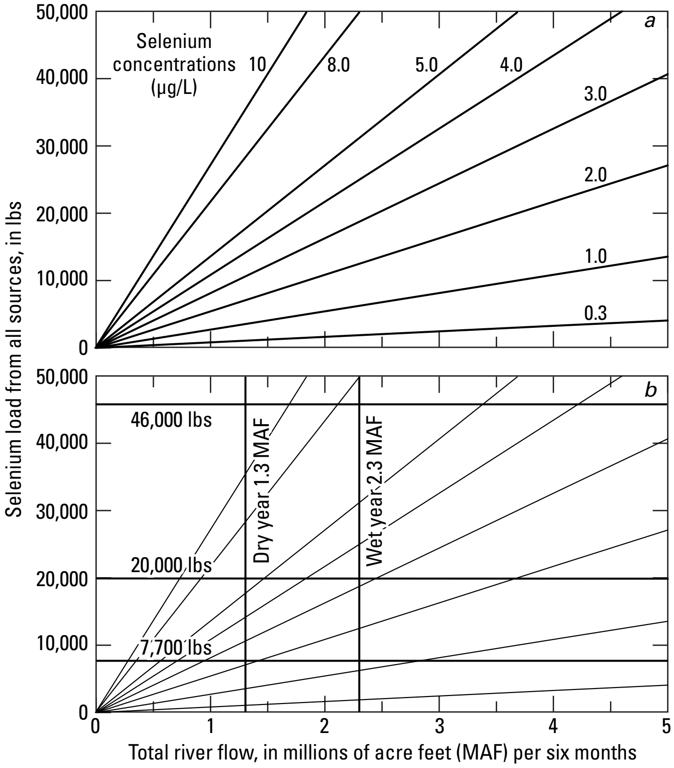

Figure 22. (*a*) Calculation of eight composite freshwater endmember selenium concentrations as derived from different combinations of total input load and total river inflow (as composited mass of water that reaches the estuary in a six-month period); and (*b*) examples of resulting wet and dry year selenium concentrations for three selenium load scenarios.

full flow in a San Luis Drain extension, then extreme concentrations are projected to occur in the Bay-Delta. Under a load of 44,880 lbs selenium per six months**,** forecasted selenium concentrations of > 6.97 µg/L at Carquinez Strait are projected during the low flow season of both wet and critically dry years.

A selenium concentration of 1 µg/L is threefold higher than presently found in the Bay-Delta in a normal rainfall year (Cutter 1989; Cutter and San Diego-McGlone, 1990; and San Francisco Bay Board, 1992a, b , also see table 18) and represents the current Canadian guideline for protection of aquatic life (Environment Canada/Health Canada, 1995; Outridge and others, 1999). This selenium concentration cannot be achieved near Carquinez Strait in the low flow season by any scenario that includes an extension of the San Luis Drain, except a load of 6,800 lbs per six months (fig. 21). In the high flow season of a wet year, concentrations forecasted at the Carquinez Strait are 0.14 to 0.94 µg/L.

An important component of a monthly analysis, not evident in a six month analysis, for the illustrated San Luis Drain extension scenario (a constant 62.5 µg/L selenium concentrations) is the very elevated selenium concentrations that result each year in the fall (fig. 19). The strong dependence of selenium contamination on climate and water demand, which, together, determine discharge to the estuary, is also evident. Concentrations in excess of 2 µg/L would extend through much of Suisun Bay and San Pablo Bay for greater than six month of the year in this drain forecast (fig.19). It is possible that the dilution assumptions employed here might understate the geographic extent of selenium distributions in projections for October. Sophisticated physical models are being developed for the Bay-Delta and could be helpful in describing such important details (for example, Monsen, 2000; Monsen and others, 2002).

Forecasts of Speciation and Transformation

Speciation of selenium in the Bay-Delta is controlled by physicochemical processes and speciation in the sources of discharge (see previous discussion; Cutter and Bruland, 1984; Cutter, 1989; Luoma and others 1992). Speciation will change as sources change in importance. Prior to 1998, refinery discharges of selenite were a principal influence on speciation and bioavailability. Refinery discharges declined in July 1998. A lower proportion of the total selenium was selenite in the late 1990s than in the 1980s (Cutter and Cutter, 2004). It is likely that the proportion of selenate discharged to the Bay-Delta would increase if a San Luis Drain extension is built or if/when San Joaquin River inflows to the Bay-Delta increase. Biotransformation to Se(-II) and/or sediment accumulation and recycling of Se(-II) in the Bay-Delta are highly likely under increased San Joaquin River selenium load if the transformation conditions prevalent at present in the Bay-Delta are operable on the San Joaquin River discharge. This influx of Se(-II) into the Bay-Delta could be accentuated if marshes are restored in areas subjected to inflows from the San Joaquin River or a San Luis Drain extension.

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

Ultimately, forecasts of selenium speciation should be derived from biogeochemical kinetic speciation models. As discussed previously, thermodynamic equilibrium approaches are not suitable for selenium systems because of the dynamic nature of biological reactions that control transformation and transport processes within water, particulate matter, and organisms. A model of internal regenerative cycling of selenium in the Pacific Ocean focused on uptake, particulate transport, and the kinetics of selenium species inter-conversions (Cutter and Bruland, 1984). A general modeling framework for selenium outlined a strategy for considering the kinetics and transfer of the different forms of selenium (Bowie and others, 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 the approach used here based on mixes of species that have been observed in nature under circumstances possible for the Bay-Delta. How each mix of species would affect transformations of dissolved selenium to particulate selenium (speciation is implicit in the choice of transformation reactions) is then forecast.

Transformation is quantitatively expressed by the distribution of selenium between particulate and dissolved forms, the K_d (see previous discussion). The effect of speciation and transformation is incorporated by using K_d's observed in previous studies (table 11) to project a ratio of total selenium typical of a given speciation regime. For each combination of K_d and speciation (the speciation/transformation regime), the form of particulate selenium observed under those circumstances is incorporated to enable a projection of overall bioavailability.

Defining speciation, transformation, and bioavailability (speciation/transformation regime)

Three sets of speciation/transformation regimes are presented below in which a specific distribution of selenium among particulate forms is assumed. These speciation and biochemical behavior patterns are used throughout progressive forecasts presented here of selenium concentrations in particulates, bivalves, and predators.

- **High Bioavailability (C1)**

  Speciation: high proportion of selenite plus organo-Se (60 percent)

  K_d: 1×10^4

  Precedent: estuarine suspended material in the Bay-Delta

  Particulate bioavailability: 60 percent high and 40 percent moderate

To bound a high bioavailability condition, Se(IV) and a portion of the Se(-II) are assumed to contribute to biotransformation to organo-Se. Preliminary studies in the late 1990s showed that as much as 60 percent of dissolved selenium was Se(IV) plus Se(-II) in Suisun Bay. Selenite has declined since refineries reduced their discharges, but organo-Se has become a larger proportion of dissolved selenium (Cutter and Cutter, 2004). In Suisun Bay, this speciation regime is accompanied by a particle/dissolved distribution (K_d) of 10^4. For example, distribution coefficients for estuarine suspended material in most of the Bay-Delta were 8.2×10^3 to 2.1×10^4, between September 1986 and October 1996. Biotransformation may explain these high K_d's. Some species of diatoms, the most common phytoplankton in the North Bay, have K_d's higher than 10^4 in laboratory experiments (Reinfelder and Fisher, 1991) (table 11). For bioavailability calculations, the form of the particulate selenium under these conditions is assumed to be 60 percent biotransformed and 40 percent oxidized material of moderate bioavailability. Biologically, this speciation/transformation regime is most relevant to water column-feeding species of consumer organisms.

- **Moderate Bioavailability (C2)**

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

  K_d: 3×10^3

  Precedent: typical of shallow-water estuarine sediments or marine waters

  Particulate bioavailability: 60 percent moderate and 40 percent high

If sources of selenium change, it is possible that the proportion of selenium as Se(IV) + Se(-II) in the Bay-Delta will decline to <60 percent. Even if the proportion of Se(IV) and Se(-II) remains high, it is possible that the bioavailability of Se(-II) is less than that of Se(IV). To account for either of these possibilities, 40 percent of total selenium is assumed to contribute to biotransformation at the rate of Se(IV). A speciation regime of 40 percent biotransformable selenium and 60 percent less reactive selenium 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 3×10^3 to 1×10^4 (Velinsky and Cutter, 1991; Cutter and Cutter, 2004; Doblin and others, 2006) (table 11). This speciation and K_d combination is assumed to result in particulate selenium that is 60 percent in a form of moderate bioavailability [detrital Se(-II) or particulate Se(IV) + (VI)]; and 40 percent in a form of high bioavailability (biotransformed organo-Se). Biologically, this speciation/transformation regime applies to biota that predominantly ingest sediments with concentrations diluted by non-transformed load.

- **Low Bioavailability (C3)**

  Speciation: predominantly Se(VI)

  K_d: 1×10^3

  Precedent: Systems such as an area of a wetland near a discharge site of selenate-dominated irrigation drainage waters

  Particulate bioavailability: 50 percent low, 40 percent moderate, and 10 percent high

This condition assumes that most of the selenium entering the Bay-Delta remains as Se(VI). Selenate is transformed, but the K_d'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 discharges at Benton Lake, Montana, where K_d's are about 10^3 (Zhang and Moore, 1996). This value also is at the lowest end of the range of distribution coefficients characterizing Bay-Delta sediments and is probably the most optimistic scenario that can be hoped for, in terms of generating particulate selenium and ultimately biological effects. For forecasting bioavailability, this material is assumed to be 50 percent slurry-generated Se(0) of relatively low bioavailability, 40 percent oxidized material of moderate bioavailability, and 10 percent organo-Se of high bioavailability. This speciation/transformation regime would apply most readily to deposit feeding benthos, especially those feeding within sediments.

In general, it is recognized in the approach presented here that the K_d-concept has limitations and that there are uncertainties about future speciation should a San Luis Drain extension begin discharging selenium loads to the Bay-Delta. Nevertheless, the three speciation/transformation regimes described above are likely to fully bound the possibilities. Using these regimes, at the least, ranges of particulate selenium concentrations and particulate forms can be forecast.

Comparison of forecasted particulate concentrations to observed Bay-Delta conditions

It is instructive to visually compare forecasts using the three K_d's presented above to existing data for the Bay-Delta. In figure 23, concentrations observed in the Bay-Delta for suspended particulate selenium concentrations are plotted against observed dissolved concentrations (Cutter, 1989; Cutter and San Diego-McGlone, 1990; Cutter and Cutter, 2004; Doblin and others**,** 2006). Lines describing predicted particulate concentrations using K_d's of 1×10^3 and 1×10^4 are superimposed on the plots. A K_d of 1×10^3 is too low to describe any of the existing suspended sediment data making it a low probability condition. The October 1996 data (the highest concentrations observed in any survey) exceed a K_d 1×10^4 and the September 1986 data fall between the two values. In figure 24, similar data are presented in a different way. Particulate concentrations are predicted from dissolved concentrations that occurred landward to seaward in the Bay-Delta in October 1996. The three different K_d's presented above describe three different trend lines for particulate concentrations through the estuary. The observed October 1996 particulate data is superimposed on these predictions. The superimposed data illustrate that a K_d of 1×10^4 is the best choice for this data set. A K_d between 3×10^3 and 1×10^4 would best fit the September 1986 data, if it were plotted similarly. The three K_d's used for these predictions (fig. 24) were, of course, developed based on 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 (all values are dry weight concentrations)

Sediment guidelines

As discussed previously, the principal risk of sediment to fish and birds is through the aquatic food chain. Sediment guidelines are based on sediment concentrations as predictors of adverse effects through the food chain. Proposed sediment guidelines for selenium (μg/g in particulate material or sediment, dry weight) provide a context to evaluate forecasted particulate selenium concentrations. Skorupa (1998b) provided a compilation of background and biotic thresholds and effects levels for sediment. Canton and Van Derveer (1997) and Van Derveer and Canton (1997) recommended sediment criteria based on data from streams in Colorado and a relatively insensitive community analysis (Hamilton and Lemly, 1999). Luoma and others (1992) studied bioavailability of particulates in an estuarine environment, including modeling sediment ingestion and selenium tissue burdens in the clam *M. balthica*.

The guidelines given below are based on few studies that include bioaccumulation as part of a comprehensive analysis. Most guidelines do not specify in detail whether the tested material was bed, fine, or suspended sediment or whether the collection method attempted to include living material (for example, diatoms) as an indicator of the degree of recycled material that is available as food for lower food web organisms. Assessing spatial variability and careful matching of invertebrate and sediment samples also are of importance in interpreting effects. Thus, concentrations in sediment provide one line of evidence of how selenium might affect foodwebs and ultimately predators. As discussed previously, low certainty results if a hazard evaluation is based on one line of evidence. The approach presented here, the Bay-Delta selenium model, attempts to rectify that situation and provide a systematic approach that links all relevant processes to forecast ecological effects from selenium on aquatic food webs. As such, the approach could provide a framework for developing new protective selenium foodweb guidelines, including sediment or particulate matter guidelines. The site specific guideline included below, addresses to some degree that interconnectedness.

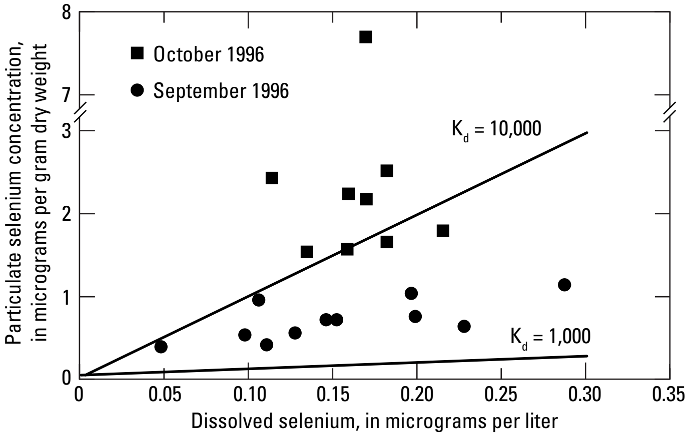

Figure 23. Observed suspended particulate selenium concentrations as a function of observed total dissolved selenium concentrations during September 1986 and October 1996, with predicted particulate concentrations (using K_d's of 1,000 and 10,000) superimposed on the plot.

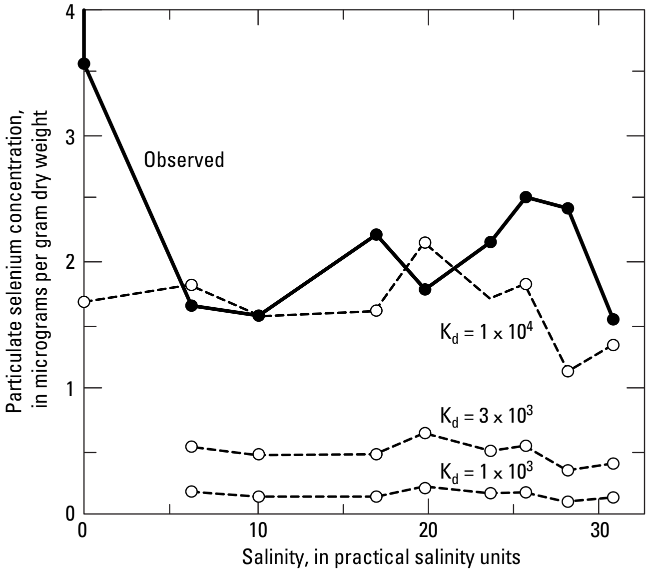

Figure 24. Observed (October 1996) and predicted particulate selenium concentrations as occurring landward (zero practical salinity units) to seaward (35 practical salinity units) in the Bay-Delta projected from dissolved concentrations (see figure 23) and three different K_d's (1,000; 3,000; and 10,000).

Compiled guidelines for sediment are:

- **low risk: 0.4 to 1 µg/g.** A concentration of 0.5 µg/g was used as an alert level for possible sediment contamination in the San Joquin Valley (Drainage Program, 1990b). A no effect boundary for birds in a specialized environment (nesting at shallow terminal evaporation ponds) was reported at 0.4 µg/g and the minimum total response boundary (100 percent lethality boundary) was reported at1 µg/g (Skorupa, 1998b).

- **site-specific for Bay-Delta: 1.5 µg/g**. As discussed previously, site-specific protective guidelines depend on both bioavailabity of particulates and the specifics of food webs (for the Bay-Delta, the species of clam). Luoma and others (1992) showed that particulate concentrations in the range of 1.5 µg/g could result in the deposit-feeding bivalve concentrations (9 to 10 µg/g) that have a high certainty of producing toxicity in fish and birds.

- **sedimentary level of concern: 2 µg/g.** Van Derveer and Canton (1997) proposed a preliminary sedimentary selenium toxicity threshold (10th percentile for effects) of approximately 2.5 µg/g. Engberg and others (1998) suggest levels of 2 to 4 µg/g are of concern for adverse effects in freshwater environments.

- **observed effect concentration: 4.0 µg/g.** Adverse effects were always observed at selenium concentrations >4 µg/g (Canton and Van Derveer (1997). Concentrations in excess of this value have a high certainty of producing toxicologic and reproductive effects (Engberg and others, 1998).

These guidelines may not be, individually, realistic indications of ecological risk, but are used in this report as reference points to provide context.

Forecasts of particulate selenium concentrations

Tables F3 to F5 in appendix F show detailed selenium particulate concentrations both at the head of the estuary (composite freshwater endmember concentration) and Carquinez Strait for four San Luis Drain extension load scenarios and two San Joaquin River scenarios under three different climate regimes (also see tables 19 through 21 for composite freshwater endmember concentrations). Speciation/transformation regimes typical of suspended sediments (C1), shallow-water sediments (C2), and inefficient transformation (C3) are used in each set of calculations. Table 24 summarizes particulate selenium concentrations at the head of the estuary for these load scenarios. Forecasts are compared to data reflective of conditions prior to refinery cleanup.

Forecasts using a San Luis Drain extension discharging 6,800, 18,700, or 44,880 lbs selenium per six months during the low flow season in a critically dry year show that (table 24):

- all releases to the Bay-Delta under the three assumed speciation/transformation regimes (C1, C2, and C3) result in particulate concentrations >2.0 µg/g at the head of the estuary.

- only under the lowest discharge assumption (6,800 lbs per six months) combined with the least likely speciation/transformation regime (C3), would a particulate selenium value (2.07 µg/g) be observed below 4.0 µg/g. In all other cases the certainty of effects would be high.

- if the speciation/transformation regime of suspended material was that observed in all existing studies of the Bay-Delta (C2), projected loads of selenium result in particulate selenium concentrations in upper Suisun Bay of 6.2 to 35.6 µg/g. The certainty of effects would be high to very high.

Under all but the most optimistic speciation/transformation conditions, load scenarios with management of drainage quantity and quality (6,800 to 18,700 lbs per six months) yield particulate selenium concentrations in the upper estuary that exceed 4.0 µg/g. Selenium concentrations in particulates of approximately 12 to 119 µg/g are possible if management is not a priority (44,880 lbs per six months).

Forecasts for a San Luis Drain extension during the low flow season of a wet year yield particulate selenium concentrations that are approximately 60 percent of those projected for a critically dry year (table 24) if:

- a load of 6,800 lbs is discharged in six months. Under this approach, the projected range of selenium particulate concentrations is 3.6 to 12 µg/g under the most likely selenium speciation/transformation regimes (C1 and C2).

- the drain is managed at full flow capacity, with selenium concentrations like those in the Grassland Bypass Channel Project (18,700 lbs per six months). The forecasted range of particulate concentrations is 9.0 to 30 µg/g under C1 and C2 speciation/transformation regimes. The latter concentration is more than seven times higher than the level at which toxicologic and reproductive effects are likely.

Under a C3 speciation/transformation regime, only loads in the range of the lowest load scenario (6,800 lbs per six months) would result in particulate selenium 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 selenium data trends presented on a monthly basis (figs. 19 and 20; appendix F, tables F1 and F2)].

Discharges of 6,800, 18,700, or 44,880 lbs per six months released from a San Luis Drain extension into the Bay-Delta during the high flow season of a wet year results in exceedances of 4 µg/g only if a speciation/transformation regimes typical of suspended sediment (C1) characterize transformations (table 24). However, it should be recognized that the projected concentrations are averages over the six-month high flow period. Flows are especially 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 San Luis Drain extension are most likely to add to the selenium load in the estuary.

Forecasts for a *targeted* load (3,500 lbs selenium per six months) using the San Joaquin River for conveyance show that (table 24):

- during the low flow season, forecasted particulate selenium concentrations is in excess of 4.0 µg/g if speciation/transformation regimes are typical of suspended sediment (C1), but not if a shallow-water sediment-type transformation prevailed (C2).

- during the high flow season of a wet year, forecasted particulate selenium concentrations remain below 1.5 µg/g for all three speciation/transformation regimes considered.

The forecast for a *restoration* scenario in the San Joaquin River shows that (table 24):

- during the high flow season of a wet year, particulate selenium concentrations under all three speciation/transformation regimes are similar to those that would occur during the *targeted* load scenario (below 1.5 µg/g).

- during the low flow season in a critically dry year or a wet year, particulate selenium concentrations are less than those that would occur during a *targeted* load scenario and remain below 2.5 µg/g under all three speciation/transformation regimes.

All San Luis Drain discharge scenarios predict particulate selenium concentrations greater than those forecast for prior to refinery cleanup (table 24). Particulate selenium concentrations lower than those modeled prior to refinery cleanup are predicted to occur:

- in the *restoration* scenario for the San Joaquin River in all modeled water year types and seasons; and

- in the San Joaquin River *targeted* load scenario during the high flow season of a wet year.

Cumulative summary

Progressive forecasts for the head of the estuary show selenium loads, waterborne selenium concentrations, and particulate selenium concentrations (table 25). Three alternative speciation/transformation regimes are illustrated [suspended sediment (C1); shallow-water sediment (C2); and inefficient transformation (C3)] for each endmember concentration. Load scenarios are 18,700 lbs released during six months through a San Luis Drain extension or of approximately 3,500 lbs released during six months through the San Joaquin River (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 speciation/transformation regimes in determining particulate concentrations. Clearly, benefit would come from knowing these dissolved to particulate transformations with more certainty for the Bay-Delta.

For a San Luis Drain load scenario of 18,700 lbs per six months (table 25), it is notable that exceedance of the USEPA waterborne criterion of 5 µg/L at the head of the estuary (composite freshwater endmember concentration) in the low flow season of a critically dry year is always accompanied by

Table 24. Forecasts of selenium concentrations in particulate matter at the head of the estuary under projected selenium load scenarios, identified speciation/transformation regimes, and different climatic conditions.

[C1 = K_d of 1×10^4, typical of suspended sediment; C2 = K_d of 3×10^3, typical of shallow-water bed sediment; C3 = K_d of 1×10^3, typical of inefficient transformation]

Scenario	Selenium concentrations in particulate material (µg/g dry weight)						
	Past	San Luis Drain extension				San Joaquin River	
	Prior to refinery cleanup	Half capacity at 50 µg/L	Full capacity at 62.5 µg/L	Full capacity at 150 µg/L	Full capacity at 300 µg/L	*Targeted* Load	Restoration 0.5 µg/L
Wet year/high flow							
Load (lbs per six months)	–	6,800	18,700	44,880	89,760	3,500	3,060
C1 (1×10^4)	2.2	2.8	5.1	10.2	18.8	1.2	1.1
C2 (3×10^3)	0.66	0.84	1.53	3.06	5.6	0.36	0.33
C3 (1×10^3)	0.22	0.28	0.51	1.02	1.88	0.12	0.11
Wet year/low flow							
Load (lbs per six months)	–	6,800	18,700	44,880	89,760	3,400	1,020
C1 (1×10^4)	3.9	12.1	29.9	69.7	138	5.7	2.3
C2 (3×10^3)	1.2	3.63	8.97	20.9	41.4	1.71	0.39
C3 (1×10^3)	0.39	1.21	2.99	6.97	13.8	0.57	0.23
Critically dry year/low flow							
Load (lbs per six months)	–	6,800	18,700	44,880	89,760	3,400	381
C1 (1×10^4)	5.3	20.7	50.7	118.7	235	8.6	2.4
C2 (3×10^3)	1.6	6.21	15.2	35.6	70.6	2.58	0.72
C3 (1×10^3)	0.53	2.07	5.07	11.9	23.5	0.86	0.24

exceedance of a sediment guideline (4 µg/g) in which effects are a certainty, no matter what the selenium transformation. Also under this load scenario, the USFWS recommended waterborne criterion of 2.0 µg/L is exceeded for the low flow season of a wet year. For this same climate regime, at an inefficient selenium transformation (C3) and a composite freshwater endmember selenium concentration of 2.0 µg/L, particulate selenium concentrations would exceed a guideline with a high certainty of producing effects based on site-specific factors (1.5 µg/g, see previous discussion). At typical estuarine suspended and shallow-water sediment transformations (C2 and C3), forecasted particulate selenium concentrations are > 4 µg/g. Even during high inflows in a wet year, a 4.0 µg/g guideline is exceeded if a K_d typical of October 1996 (K_d of 1×10^4) occurs.

For the San Joaquin River *targeted* load scenario of 3,500 lbs per six months (table 25), composite freshwater endmember selenium concentrations remain below 1 µg/L. However, particulate selenium concentrations only remain below 1.5 µg/g for an inefficient speciation/transformation regime (C3) or during the high flow season of a wet year. During low flow seasons of both wet and dry years, particulate selenium concentrations exceed 1.5 µg/g, and in the case of a speciation/transformation regime for a productive estuarine system (C1), could exceed 4 µg/g.

In summary, selenium loads, river inflows, speciation, and dissolved/particulate transformation rates are critical to determining particulate selenium concentrations and thus important determinants of the ecological effects of a discharge conveyed directly to the Bay-Delta. Most feasible San Luis Drain extension discharges during low flow periods result in concentrations of particulate selenium that have a high certainty of producing toxicologic and reproductive effects (see previous descriptions). This is especially true if the speciation/transformation regime conditions currently prevalent at present in the Bay-Delta (C2 and C3) are operable on proposed discharges from an extension of the San Luis Drain. Only during wet years and high flows is a 1.5 µg/g selenium particulate material guideline not exceeded, and then only when transformations are inefficient. Note also that this guideline was exceeded during conditions prior to refinery cleanup All forecast particulate selenium concentrations exceed those forecast for conditions prior to refinery cleanup, except under the *targeted* load San Joaquin River scenario during the high

Table 25. Cumulative summary of forecasts of selenium concentrations in a composite freshwater endmember and particulate matter at the head of the estuary under projected selenium load scenarios, identified speciation/transformation regimes, and different climatic conditions.

Climatic conditions	Composite fresh-water endmember selenium (µg/L)	Particulate selenium (µg/g dry weight)		
		C3 (K_d=1×10^3)	C2 (K_d=3×10^3)	C1 (K_d=1×10^4)
San Luis Drain extension load of 18,700 lbs per six months (full capacity at 62.5 µg/L selenium)				
Wet Year/ High Flow	0.46	0.5	1.5	5.1
Wet Year/ Low Flow	3.0	3.0	9.0	30.0
Critically Dry Year/ Low Flow	5.1	5.1	15.2	50.7
San Joaquin River *targeted* load of 3,590 lbs per six months for a high flow season (1.2 µg/L selenium); 3,400 lbs per six months for a low flow season (2.5 µg/L selenium)				
Wet Year/ High Flow	0.12	0.12	0.36	1.2
Wet Year/ Low Flow	0.57	0.57	1.71	5.7
Critically Dry Year/ Low Flow	0.86	0.86	2.58	8.6
Conditions prior to refinery cleanup				
WetYear/ High Flow	0.22	0.22	0.66	2.2
Wet Year/ Low Flow	0.39	0.39	1.2	3.9
Critically Dry Year/ Low Flow	0.53	0.53	1.6	5.3

flow period of a wet year. The *restoration* scenario for the San Joaquin River results in forecasted particulate selenium concentrations lower than those forecasted for conditions in the Bay-Delta prior to refinery cleanup

Other possible scenarios

1. **No reaction of Se(VI).** If discharges of 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 (1) dissimilatory reduction to sedimentary Se(0) not occur in sediments or wetlands; and (2) selenate uptake by primary producers not take place. Biotransformation of selenium is, indeed, minimized in at least some flowing water (lotic or river/stream) systems, compared to wetlands. However, there is no precedent in nature for a complete absence of selenium biotransformation to particulate concentrations. At least a K_d of 0.5 × 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.

2. **Direct San Luis Drain discharge of suspended particulate selenium from an extension of the San Luis Drain.** Input of suspended particulate material containing elevated concentrations of selenium is likely from a San Luis Drain extension directly into the Bay-Delta. The San Luis Drain during its operation from 1981 to 1985 acted as a partial treatment facility by removing selenium 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 selenium have accumulated in the San Luis Drain to date and are likely to continue to accumulate during its renewed use by the Grassland subarea to convey drainage to the San Joaquin River (USBR and others, 1998 and ongoing) (appendix E, tables E1 and E2). Selenium concentrations in San Luis Drain sediment have exceeded the hazardous selenium waste criterion for solids (100 µg/g, wet weight) at times in the past and almost all concentrations are above a sediment guideline (4 µg/g) in which effects are a certainty (see previous discussion). Re-suspension and at least some transport of those sediments during elevated flows seems a reasonable prediction should the San Luis Drain be extended to the Bay-Delta. For example, the San Luis Drain was briefly re-opened in early 1995 to relieve flooding in the western San Joaquin Valley and it acted as a conduit for discharges into Mud Slough and the San Joaquin River (Presser and Piper, 1998). Transport and dilution of such particles probably cannot be estimated with any reasonable certainty. However, the discharged particulate selenium would probably originate as primarily Se(0) and oxidation also would occur with longer residence times in suspension or in the water column. Source material also may include algal mats that could contain organo-Se [bioavailable Se(-II)]. The following conditions and calculations for direct discharge of suspended particulate selenium from a San Luis Drain extension are instructive, but speculative. They illustrate how even small inputs of existing contaminated San Luis Drain sediment could affect the Bay-Delta.

   a. If a San Luis Drain extension inflow is 5 percent of river inflow to the Bay-Delta and suspended material concentrations (amounts) are similar in both the Sacramento River and the San Luis Drain (based on relative inflows in a wet year at low flow).

b. If an average particulate selenium concentration in the San Luis Drain particles is 100 µg/g and particulate selenium in the Sacramento inflows is 0.2 µg/g.

c. Then 5 percent of the particles in the Bay-Delta at the confluence of the two will be San Luis Drain particles and the selenium concentrations in the particle mixture will be:
[(0.05 × 100 µg/g) + (0.95 × 0.2 µg/g)] = 5.19 µg/g from direct particulate input.

d. During a critically dry year, particulate selenium concentrations would be twice this value.

e. Particulate selenium transformed from the dissolved selenium inputs from a San Luis Drain extension would add to these concentrations; therefore this estimate is conservative in this respect.

3. **Local hotspots.** Selenium concentration forecasts 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 (for example, Cheng and others, 1993; Monsen, 2000; Monsen and others, 2002). However, hotspots of particulate selenium contamination could develop in an ecosystem subjected to direct San Luis Drain extension discharges. Most notably, wetlands close to the discharge of a San Luis Drain extension would be likely to accumulate high concentrations of selenium.

Forecasts of Bioaccumulation in Consumer Organisms (all values are dry weight concentrations)

Calculating bioaccumulation in a generic bivalve (modeling)

A range of biological values are used in the *DYMBAM* model to calculate selenium concentrations in bivalves of the Bay-Delta (table 26). The model is for a generic bivalve (physiological constants are averages over a small range from several bivalve species, Reinfelder and others, 1997; Schlekat and others, 2000, 2002, 2004). Calculations specific to *P. amurensis* and *C. fluminea* also could be made. Some data for these species recently are available (table 26). 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 per day (estimate for many bivalves based on review of literature in Luoma and others, 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) of about 20 percent (low bioavailability) to 80 percent (high bioavailability) as a function of particle type (see below).

Combining the above factors and a range of particle transformations that affect bioavailability, bivalve bioaccumulation is cast here in terms of assimilation efficiencies (AE in percent):

- **Inefficient transformation:** Particulate forms are 50 percent Se(0) of relatively low bioavailability, 40 percent oxidized material of moderate bioavailability, and 10 percent organo-Se of high bioavailability. The AE derived from this mixture is 35 percent:
  AE1 (0.23 × 50%) + (0.4 × 40%) +
  (0.79 × 10%) = 35%

- **Shallow-water estuarine sediments:** Particulate forms are 60 percent of moderate bioavailability [detrital Se(-II) or particulate Se(IV) + (VI)]; and 40 percent in a form of high bioavailability (biotransformed organo-Se). The AE derived from this mixture is 56 percent:
  AE2 (0.40 × 60%) + (0.79 × 40%) = 56%

- **Estuarine suspended material:** Particulate forms include 60 percent biotransformed selenium of high bioavailability and 40 percent oxidized material of moderate bioavailability. The AE derived from this material is 63 percent:
  AE3 (0.79 × 60%) + (0.40 × 40%) = 63%

- **Estuarine suspended material—purely biogenic:** A fourth AE (79 percent) also is included to take into account the possibility that all suspended particulate selenium in the estuary would derive from biogenic transformation to Se(-II).
  AE4 (0.79 × 100 %) = 79%

- To complete the range of considered AE's, a fifth AE is derived for all particulate material being of a form of low bioavailability, Se(0). The AE derived is 23 percent:
  For range (0.23 × 100%) = 23%

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

Generic bivalve physiological parameters (table 26) and the *DYMBAM* model are used to forecast bioaccumulation of selenium in consumers organisms (prey) for a range of concentrations using two extremes of assimilation efficiency, 80 percent (all biotransformed) and 20 percent (all elemental selenium) (table 27). The purpose of these calculations is to verify that use of the *DYMBAM* model bracketed reasonable predictions of selenium bioaccumulation in bivalves. The

Table 26. Laboratory-derived physiological constants for selenium bioaccumulation by several species of bivalve and composite values for a generic bivalve.

[Data from Luoma and others, 1992; Reinfelder and others, 1997.]

Species	Ingestion rate (grams food/ grams tissue/day)	Assimilation efficiency (AE) (%)	Rate constant of loss (k_e) (per day)	Assimilation efficiency/rate of loss (AE/ k_e)
Oyster (*Crassostrea virginia*)	–	70 ± 6	0.07 ± 0.0008	10
Clam (*M. balthica*)	0.25	80 ±7	0.03 ± 0.001	26.7
Clam (*Mercenaria mercenaria*)	–	92 ± 2	0.01 ± 0.004	92.0
Mussel (*M. edulis*)	0.27	74 ± 8	0.02 ± 0.007	37.0
Generic bivalve (from diatom)	0.2	79	0.02	39.5
Generic bivalve (from sorbed selenium)	0.2	40	0.02	20
Generic bivalve (from elemental selenium)	0.2	23	0.02	11.5

range of particulate selenium concentrations used in the calculations spanned the concentrations of selenium determined in surveys of the brackish Bay-Delta (0.5 to 3.0 µg/g) and at the head of the Bay-Delta (0.5 to 8.0 µg/g). Three observations are of interest from forecasted bivalve concentrations during Bay-Delta conditions prior to refinery cleanup:

- The forecasted concentrations of bioaccumulated selenium in bivalves span the exact range of selenium concentrations found in bivalves in this system (figs. 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 and others, 1992; and Wang and others, 1996).

- A fourfold difference in bioaccumulation in bivalves would be expected if the particulate form of selenium changed. At the same concentration of particulate selenium, bivalves would bioaccumulate four-times more selenium from the biotransformed particulate selenium than from elemental selenium. Although this bioaccumulation is significant, the effect is relatively small compared to the effects of changing the mass of selenium in the load.

- The field validation results verify that the *DYMBAM* model will be useful in forecasting the range of consumer organism bioaccumulation under different input scenarios for selenium.

Bivalves as food for predators

The most sensitive response of ecosystems to selenium occurs in higher trophic level predators (such as birds and fish) (Ohlendorf, 1989; Hamilton and others, 1990, 2005a, b, c, d; Lemly, 1996b, c; Skorupa, 1998a). Effects on predators (see reviews in Lemly, 1998b; Skorupa, 1998a; Hamilton, 2003 and 2004; Ohlendorf, 2003) have been defined based on:

- selenium concentrations in their food

- effects on predators themselves expressed as selenium residues in tissue.

Bivalves (clams) are an important food source for the predators of interest in the present evaluation. Therefore, one type of guideline for bivalve tissues should be based on their use as a food source for fish and birds. The guidelines for food webs show the narrow difference between concentrations considered safe and those considered harmful. Marginal risk levels, which are between levels considered safe (no effect) and those considered harmful (substantive risk) are intended to provide protection for the environment in that they are based on data for sensitive endpoints and species. Guidelines for predators based on selenium in food are (also see tables 13 and 15):

- **3 – 7 µg/g in food = Level of concern range.** Selenium concentrations in predator food (invertebrate tissues) within this range are a concern for development and survival, especially for sensitive lifeforms of sensitive species (tables 13 and 15). Reviews and studies by Lemly (1993b, 1997b, and 2002) and Hamilton (2004) document a 2 to 5 µg/g selenium in diet in the field as a hazard. Ohlendorf (2003) reported a hatchability effect

Table 27. Modeled selenium concentrations in a generic bivalve when exposed to different concentrations of particulate organo-selenium or particulate elemental selenium.

[Data from Luoma and others, 1992 and Reinfelder and others, 1997. Measured particulate selenium concentrations range from 0.5 to 3 µg/g dry weight in brackish water of the Bay-Delta and 0.5 to 8 µg/g dry weight at the head of the estuary (Cutter, 1989; Cutter and Cutter, 2004).]

Particulate selenium concentration (µg/g dry wt)	Absorption efficiency (AE) (%)	Rate constant of loss (k_e) (per day)	Tissue selenium concentration at steady state (µg/g dry wt)
Exposure: particulate organo-selenium			
0.5	0.8	0.02	4.0
1.0	0.8	0.02	8.0
1.5	0.8	0.02	12.0
2.0	0.8	0.02	16.0
3.0	0.8	0.02	24.0
Exposure: particulate elemental selenium			
0.5	0.2	0.02	1.0
1.0	0.2	0.02	2.0
2.0	0.2	0.02	4.0
3.0	0.2	0.02	6.0
4.0	0.2	0.02	8.0
5.0	0.2	0.02	10.0
8.0	0.2	0.02	16.0

level of 10 percent in mallards at 4.87 µg/g selenium (confidence interval 3.56 to 5.74 µg/g) in diet based on a compilation of laboratory studies. Mortality (a less sensitive endpoint) in juvenile bluegill occurred when they were fed a diet of 5.2 µg/g during simulated winter-stress conditions in the laboratory (38 percent effect level) (Lemly, 1993b).

- **10 µg/g in food = Effects on predators a certainty.** Selenium concentrations in predator food above 10 µg/g have been conclusively implicated in adverse effects on reproduction in predators (Saiki, 1986; Hodson and Hilton, 1983; Johns and others, 1988; Heinz and others, 1989; Coyle and others, 1993; Lemly, 1985, 1993a, c, 1997b; Hamilton and others, 1990, 2000b; Heinz, 1996; Adams and others, 1998; Linville and others, 2002; Hamilton, 2003 and 2004) (also see tables 13 and 15). For example, Heinz and others (1989) produced a 43 percent reduction in healthy ducklings in laboratory feeding studies with mallards using a diet of 8 µg/g (seleno-methionine). Although these studies suggest effects begin at lower concentrations, 10 µg/g is considered here as a value of least uncertainty. When invertebrate tissues exceed 10 µg/g the expectation is strong that adverse effects are occurring in birds and fish.

- **15–20 µg/g in food = Observed conditions that coincide with extinction of some fish species and failure to produce healthy young birds.** This is the range of annual maximum concentrations of selenium in *P. amurensis* observed between 1995 and 1996 near Carquinez Strait in Suisun Bay (figs. 13 through 15). This range of selenium concentrations in diets of fish are linked to reproductive and survival effects (Skorupa, 1998a; Lemly, 2002; Hamilton, 2003 and 2004) (tables 13 and 15). Mallards fed a diet (seleno-methionine) of 16 µg/g failed to produce any healthy young birds (Heinz and others, 1989). Levels of 30 to 35 µg/g (seleno-methionine) caused total reproductive failure (catastrophic impairment) in adult bluegill (Woock and others, 1987; Coyle and others, 1993).

- **40 µg/g in food = Extinction of numerous fish species.** In field studies, all but the most tolerant populations of fish species were eliminated when selenium concentrations in invertebrates reach 40 to 100 µg/g (Lemly, 1985, 1993a, 1997c, 2002; Saiki, 1986; Saiki and Lowe, 1987; Presser and Ohlendorf, 1987; Skorupa, 1998a). Heinz and Fitzgerald (1993) found a 95 percent mortality rate when adult male mallards were fed a 40 µg/g diet (2 percent moisture) and subjected to winter stress, whereas Albers and others (1996) and Hoffman and others (1991) reported less mortality at approximately the same or a somewhat less concentrated diet in the absence of winter temperatures. Thus, values >40 µg/g might be defined as invertebrate tissue selenium concentrations where risks of extinction of multiple fish species are high.

- **100 µg/g in food = Widespread invertebrate toxicity.** Although large-scale invertebrate toxicity is probably not the most sensitive response to selenium, it could be an additional outcome of extreme selenium contamination. Rarely are invertebrates found in ecosystems where selenium concentrations in invertebrates are > 150 µg/g (Lemly, 1993a, 1997c; Saiki and Lowe, 1987). For the sake of discussion, 100 µg/g is assumed as the level of outright, broad scale invertebrate toxicity.

As previously noted for sediment selenium guidelines, these guidelines for predators based on selenium in food may not be, individually, realistic indications of ecological risk, but are used in this report as reference points for context. Again, the intent in the approach presented here, is to consider several lines of evidence to reduce uncertainty.

Forecasts of generic bivalve selenium concentrations (contamination of prey)

Details of load scenarios and calculation of generic bivalve selenium concentrations are shown for both the head of the estuary and Carquinez Strait in appendix F, tables F6 to F9. Table 28 summarizes projected concentrations in particulate material and generic bivalve tissue for four combinations of speciation/transformation regimes and generic bivalve assimilation efficienties (C1/AE4, C1/AE3, C2/AE2, C3/AE1). Forecasts are for three load scenarios (6,800; 18,700; and 44,880 lbs selenium per six months) using a San Luis Drain extension and for a San Joaquin River discharge of a *targeted* load of 3,500 lbs selenium per six months under three different climate regimes. Also included for comparison are forecasted concentrations during Bay-Delta conditions prior to refinery cleanup

Contamination of prey would be sufficient to cause widespread extinction of fish species (>40 µg/g selenium in food) during the low flow season of any year, but especially in critically dry years (table 28), if selenium transformations occur at a K_d of 3×10^3 or higher (C1 and C2) and:

- a proposed San Luis Drain extension discharges at 300 ft^3/s, even if management succeeds in limiting concentrations to 62.5 µg/L (44,880 to 18,700 lbs per six months). Some of these scenarios also could cause widespread elimination of invertebrates in addition to predicted effects on predators (>100 µg/g in food).
- a proposed San Luis Drain extension discharges at 150 ft^3/s (half capacity) with a drainage concentration of 50 µg/L (6,800 lbs per six months); and transformations and assimilations are for suspended sediment (C1/AE3 or C1/AE4).

In low flow seasons with a discharge of 18,700 lbs per six months through a San Luis Drain extension, an inefficient C3/AE1 speciation/transformation regime results in forecasted selenium concentrations in bivalves of 8.7 to 15 µg/g. In low flow seasons with a discharge of 6,800 lbs per six months through a San Luis Drain extension, a C2/AE2 speciation/transformation regime results in forecasted selenium concentrations in bivalves of 17 to 28 µg/g. In low flow seasons with a discharge of 3,500 lbs per six months through the San Joaquin River, a C2/AE2 shallow-water regime results in forecasted bivalve concentrations of 7.8 to 12 µg/g.

Lower selenium concentrations (<10 µg/g) in bivalves are forecasted under certain conditions (table 28):

- 3.5 to 6.1 µg/g: in the low flow season of both wet and critically dry years, a proposed San Luis Drain extension discharges 50 µg/L drainage at half capacity (6,800 lbs per six months); and selenium transformation and assimilations are inefficient (C3/AE1).
- 1.7 to 2.5 µg/g: in the low flow season of both wet and dry years, the San Joaquin River discharges 3,500 lbs per six months; and selenium transformation is the lowest found in any of the receiving waters previously studied; and assimilation is inefficient (C3/AE1).
- 3.9 to 0.4 µg/g: in the high flow season of wet years, a drain extension discharges of 6,800 lbs per six months or the San Joaquin River discharges 3,500 lbs per six months; and transformations are that of shallow-water sediment or are inefficient (C2/AE2 and C3/AE1).
- 6.3 to 8 µg/g: in the high flow season of wet years, the San Joaquin River discharges 3,500 lbs per six months; and transformations and assimilations are efficient (C1/AE3 or C1/AE4).

In general, San Luis Drain discharges that would meet demands for drainage pose risks to fish and bird reproduction and the risk of fish extinction from contamination of their invertebrate food (table 28). If biogeochemical conditions such as those that exist 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 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 (transformations that result in a K_d of 10^3) in that such low K_d's are not typical of the Bay-Delta. Similarly, a *targeted* load scenario for the San Joaquin River results in prey containing <10 µg/g only if transformation and assimilation are inefficient (C3/AE1) during low flow seasons. At other combinations of transformations and assimilations (C2/AE2, C1/AE3 or C1/AE4) during low flow seasons, concentrations in prey approach (8.7 µg/g) or exceed 10 µg/g (12 to 38 µg/g).

Selenium loads from 6,800 to 18,700 lbs per six months, if released during the highest flows, would result in selenium concentrations in bivalves that have a high certainty of producing adverse effects (10 µg/g) only if the most efficient speciation/transformation regime (C1) were observed (that is, if the particulate selenium 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 selenium 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 and others, 1979, 1985; Nichols and others, 1986; Peterson and others, 1989). Also during high inflows, highly contaminated particulate material from either the San Joaquin River or the San Luis Drain is most likely to add to the selenium load in the estuary (although, at present, suspended particulates are not typically highly contaminated during high inflows).

For comparison, forecasted selenium concentrations in bivalves during conditions in the Bay-Delta prior to refinery cleanup are (a) above the 40 µg/g extinction guideline during the low flow season of a critically dry year at a combination of inefficient transformation and high assimilation efficiency (C3/AE4); and (b) above the 10 µg/g guideline where effects are a certainty at a combination of moderate transformation and assimilation efficiency for shallow-water sediments (C2/AE2). During the low flow season of a wet year, 10 µg/g is exceeded

Table 28. Summary of forecasts of selenium concentrations in a generic bivalve at the head of the estuary under projected selenium load scenarios, identified speciation/transformation regimes, bivalve assimilation efficiencies (AE's), and different climatic conditions.

[C1 = K_d of 1×10^4, typical of suspended sediment; C2 = K_d of 3×10^3, typical of shallow-water bed sediment; C3 = K_d of 1×10^3, typical of inefficient transformation. AE4 = 0.8; AE3 = 0.63; AE2 = 0.55; and AE1 = 0.35.]

Scenario	Particulate selenium/bivalve selenium (µg/g dry weight)				
	Past	**San Luis Drain extension**			**San Joaquin R.**
	Prior to refinery cleanup	**Half capacity at 50 µg/L**	**Full capacity at 62.5 µg/L**	**Full capacity at 150 µg/L**	***Targeted* load**
Wet year during high flow season					
Load (lbs per six months)	–	6,800	18,700	44,880	3,500
C1 and AE4	2.2/22	2.8/19	5.1/34	10/68	1.2/8.0
C1 and AE3	2.2/17	2.8/15	5.1/27	10/54	1.2/6.3
C2 and AE2	0.66/4.5	0.84/3.9	1.5/7.0	3.1/14	0.36/1.7
C3 and AE1	0.22/0.96	0.28/0.8	0.5/1.5	1.0/3.0	0.12/0.4
Wet year during low flow season					
Load (lbs per six months)	–	6,800	18,700	44,880	3,400
C1 and AE4	3.9/39	12/81	30/199	70/465	5.7/38
C1 and AE3	3.9/31	12/64	30/157	70/366	5.7/30
C2 and AE2	1.2/8.0	3.6/17	9.0/41	21/96	1.7/7.8
C3 and AE1	0.39/1.7	1.2/3.5	3.0/8.7	7.0/20	0.57/1.7
Critically dry year during low flow season					
Load (lbs per six months)	–	6,800	18,700	44,880	3,400
C1 and AE4	5.3/53	21/138	51/338	119/793	8.6/57
C1 and AE3	5.3/42	21/109	51/266	119/625	8.6/45
C2 and AE2	1.6/11	6.2/28	15/70	36/163	2.6/12
C3 and AE1	0.53/2.3	2.1/6.1	5.1/15	12/35	0.9/2.5

at two combinations of efficient transformation and assimilation efficiency (C1/AE3 and C1/AE4). Even during high flows in wet years, this high reactivity produces prey with selenium concentrations > 10 µg/g.

Effects on predators based on selenium concentrations in food

Two scenarios, one for a San Luis Drain extension load of 18,700 lbs selenium per six months and one for a San Joaquin River *targeted* load of approximately 3,500 lbs per six months, are taken forward to progressively link uptake by bivalves and effects on predators (table 29). Forecasts are shown for three climate regimes and for three combinations of transformations and assimilation efficiencies previously illustrated (C1/AE3, C2/AE2, and C3/AE1). This cumulative summary shows waterborne, particulate, and bivalve selenium concentrations at the head of the estuary (composite freshwater endmember concentration). Forecasted invertebrate selenium bioaccumulation is compared to guidelines for effects on fish and birds from contaminated food. In the case presented here, clams are assumed to constitute that food.

Forecasts for a San Luis Drain extension scenario of 18,700 lbs selenium per six months show that (table 29):

- Selenium concentrations at the head of the estuary are projected to reach the USEPA criterion of 5 µg/L, on average, during the low flow season of a critically dry year. At the level of this criterion, effects on fish (predator) populations from selenium contaminated food (15 to 266 µg/g) would be expected, no matter what the efficiency of the transformation or assimilation for selenium in the food web (concentrations posing a serious risk would be reached under all feasible biogeochemical conditions).

- Selenium concentrations at the head of the estuary are projected to fall between the USEPA criterion and the USFWS recommended criterion of 2 µg/L in the low flow season of a wet year. Bioaccumulation would not produce 10 µg/g in food under these conditions if selenium is inefficiently transformed and assimilated. However, at a typical estuarine $K_{d,}$ bioaccumulation in bivalves would result in exceedance of both the 10 µg/g dietary guideline where effects are a certainty and a 40 µg/g extinction guideline, thus threatening an array of fish and birds in the estuary. So, in the most likely circumstances (those with precedent in the estuary) significant risk exists.

- Even during high inflows (high flow season in a wet year), effects on predators are expected if a K_d 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 selenium per six months, San Luis Drain discharges usually result in forecasted selenium concentrations in water, particulate matter, and prey (bivalve) that exceed guidelines with a high certainty of producing adverse effects during the six months or more of each year when river inflows are reduced (table 29). This condition is the most likely if a transformation prevalent at present in the Bay-Delta is operable in the future. Biogeochemical transformation rates and assimilation efficiencies are critical determinants of the degree of contamination in food of predators in the Bay-Delta and these factors need to be better understood.

The projection for the San Joaquin River *targeted* scenario (about 3,500 lbs selenium per six months) shows that (table 29):

- Under the most likely biogeochemical conditions (speciation/transformation regime C2) risks to predators are greatly reduced compared to San Luis Drain discharge scenarios. Invertebrate concentrations of selenium would exceed the 10 µg/g dietary guideline where effects are a high certainty in critically dry years. In the low season of a wet year, concentrations in clams still reach 7.8 µg/g, a level with a high certainty of affecting sensitive species. Risk at this or at inefficient transformation (C3) would be reduced in intensity compared to prior to refinery cleanup, based on contamination of bivalve prey.

- If K_d's are like those often observed for suspended material in the Bay-Delta, contamination of food would be sufficient to indicate a high risk of toxicity (>10 µg/g) and fish extinctions (>40 µg/g) during the low flow season of both wet and critically dry years. Under these same conditions in a high flow season of a wet year, selenium concentrations in clams would reach 6.3 µg/g.

These 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 (all values are dry weight concentrations)

Choice of predators

Forecasts of selenium concentrations in tissue that would result from different selenium loads scenarios are developed for white sturgeon, surf scoter, and scaup (greater and lesser). Three reasons for this choice of species are:

- These are the species for which the most data is available for the Bay-Delta (the *Selenium Verification Study*: White and others, 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 selenium, and thus seem to receive the highest internal exposure. Changes in selenium exposures in the Bay-Delta food web should have the greatest effect on concentrations of selenium in these species.

- The fish and birds with the greatest selenium 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 selenium are the first to disappear from contaminated reservoirs (Lemly, 1995, 1996a).

Relation of selenium concentrations in bivalves to selenium concentrations in predators

As discussed previously, pharmacokinetic models are the optimal approach for forecasting how changes in selenium 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 tissue concentration to bioaccumulation by prey (food)(table 12; figs. 16 and 17). Urquhart and Regalado (1991) determined selenium in white sturgeon, surf scoter, greater scaup, and lesser scaup at a number of times and locations when they or others also determined selenium in bivalves (tables 30 and 31). The bivalve *C. fluminea* was collected from 1987 to 1990 in Suisun Bay (White and others 1987, 1988, 1989; Urquhart and Regalado, 1991). Johns and

Table 29. Cumulative summary of forecasts of selenium concentrations in a composite freshwater endmember, particulate material, and a generic bivalve at the head of the estuary under projected selenium load scenarios, identified speciation/transformation regimes, bivalve assimilation efficiencies (AE's), and different climatic conditions.

[C1 = K_d of 1×10^4, typical of suspended sediment; C2 = K_d of 3×10^3, typical of shallow-water bed sediment; and C3 = K_d of 1×10^3, typical of inefficient transformation. AE1 = 0.35; AE2 = 0.55; and AE3 = 0.63.]

Climatic conditions	Composite freshwater endmember selenium (µg/L)	Particulate selenium/bivalve selenium (µg/g dry weight) C3 and AE1	Particulate selenium/bivalve selenium (µg/g dry weight) C2 and AE2	Particulate selenium/bivalve selenium (µg/g dry weight) C1 and AE3
San Luis Drain extension load of 18,700 lbs per six months (full capacity, 62.5 µg/L selenium)				
Wet year during high flow season	0.5	0.5/1.5	1.5/7	5.1/27
Wet year during low flow season	3.0	3.0/9	9.0/41	30/157
Critically dry year during low flow season	5.1	5.1/15	15.2/70	51/266
San Joaquin R. targeted load (3,590 lbs per six months for a high flow season, 1.2 µg/L selenium; 3,400 lbs per six months for a low flow season, 2.5 µg/L selenium)				
Wet year during high flow season	0.12	0.12/0.4	0.36/1.7	1.2/6.3
Wet year during low flow season	0.57	0.57/1.7	1.7/7.8	5.7/30
Critically dry year during low flow season	0.86	0.86/2.5	2.6/12	8.6/45
Conditions prior to refinery cleanup				
Wet year during high flow season	0.22	0.22/0.96	0.66/4.5	2.2/17
Wet year during low flow season	0.39	0.39/1.7	1.2/8.0	3.9/31
Critically dry year during low flow season	0.53	0.53/2.3	1.6/11	5.3/42

others (1988) also 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). *P. amurensis* invaded North Bay initially in 1986, and by the late 1980s was established as the dominant bivalve in the ecosystem. No data for selenium concentrations in *P. amurensis* were collected until 1995; but, average selenium concentrations from 1995 through 1996 in this species might be used to estimate concentrations in 1990 (Linville and others, 2002).

The bivalves discussed above are assumed here as a major food source for surf scoter, greater scaup, lesser scaup, and white sturgeon during the period 1986 to 1990. Figure 25 shows relations between bivalve selenium concentrations and selenium in the livers and flesh of these predators. Each data point represents data from a common year and common location (table 30). Average selenium concentrations in the liver and flesh of white sturgeon, surf scoter, greater scaup, and lesser scaup are significantly and strongly correlated with average selenium concentrations in bivalves. If data for *P. amurensis* are used to match the predator data in 1990, the correlation remains strong. The 1990 concentrations in *C. fluminea* are not as strongly correlated with the predators as in other years , but *P. amurensis* was the predominant benthos in 1990 in both San Pablo Bay and Suisun Bay.

Regression equations developed from data in tables 30 and 31 are used to forecast selenium concentrations in predators under different load scenarios and climate regimes employed previously. In table 30, the average bivalve selenium concentration was matched to the average tissue selenium concentration for white sturgeon, surf scoter, greater scaup, and lesser scaup. Table 31 represents a further regression of the data. In this regression, the average for all bivalves for each year of data for North Bay or Humboldt Bay is regressed for a specific predator. It is recognized that the uncertainty in this calculation is substantial because of a linear extrapolation from a small set of available data. Nevertheless, the calculation adds an important and highly relevant perspective to the forecasts presented earlier. Once these selenium concentrations are forecasted they can be compared to known adverse effects guidelines for selenium concentrations in tissues of birds and fish (see previous discussion and tables 14 and 15). This line of evidence is a second demonstration, in addition to concentrations in food, of how selenium might affect predators in the system.

Forecasts of selenium concentrations in predators

A range of hepatic (liver) concentrations of selenium in white sturgeon, surf scoter, greater scaup, and lesser scaup result from regression with bioaccumulated selenium in bivalves (table 32) . Two possible selenium load scenarios (18,700 lbs per six months for a San Luis Drain extension discharge and approximately 3,500 lbs selenium per six months for a *targeted* San Joaquin River discharge) are illustrated. The forecasts are for the low flow season of a critically dry year, which is the most relevant time period for Bay-Delta migratory predators (see discussion below). The forecasts include consideration of three possible combinations of speciation/transformation regimes and generic bivalve assimilation efficiencies (C1/AE3, C2/AE2, and C3/AE1). A range of concentrations in liver tissue (10 to 18 µg/g) associated with adverse effects on reproduction in birds and fish (tables 14 and 15) can be applied to forecasted concentrations. As previously noted for sediment and dietary selenium guidelines, these guidelines for predators based on tissue may not be, individually, realistic indications of ecological risk, but are used in this report as reference points to provide context.

White sturgeon, surf scoter, greater scaup, and lesser scaup are all in the estuary during the fall and early winter, when selenium 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 selenium concentrations in bivalves in response to higher river inflows, so in most years that have been studied, elevated selenium concentrations in bivalves extend into February or March. A further lag is expected in the response of predators to changing selenium concentrations in their food. Thus, the burdens of selenium these migratory predators would carry as they leave the Bay-Delta would probably be reasonably close to those forecasted in table 32. The low flow condition forecasts may depict the high-end of risk to these animals, but that is an ecologically reasonable expectation of exposure.

Selenium concentrations in tissues of predators are well above adverse effects guidelines (even when full latitude is given for uncertainties about linkages between tissue concentrations and effects) when a load of 18,700 lbs selenium per six months is released from a San Luis Drain extension during the low flow season of a critically dry year. There is no condition when a San Luis Drain extension carrying such loads would not greatly threaten these species. The San Joaquin River *targeted* load of approximately 3,500 lbs per six months also threatens these species if partitioning of selenium follows the suspended sediment or shallow-water sediment partitioning observed in the past. If partitioning to particulate selenium follows a K_d typical of estuarine shallow-water sediment, bivalve bioaccumulation is forecasted as similar to that which probably existed prior to refinery cleanup The resultant forecast of risk is thus similar to that forecasted to exist prior to cleanup This forecast is another line of evidence that the *targeted* load of 3,500 lbs selenium per six months, if conveyed to the Bay-Delta by the San Joaquin River, would

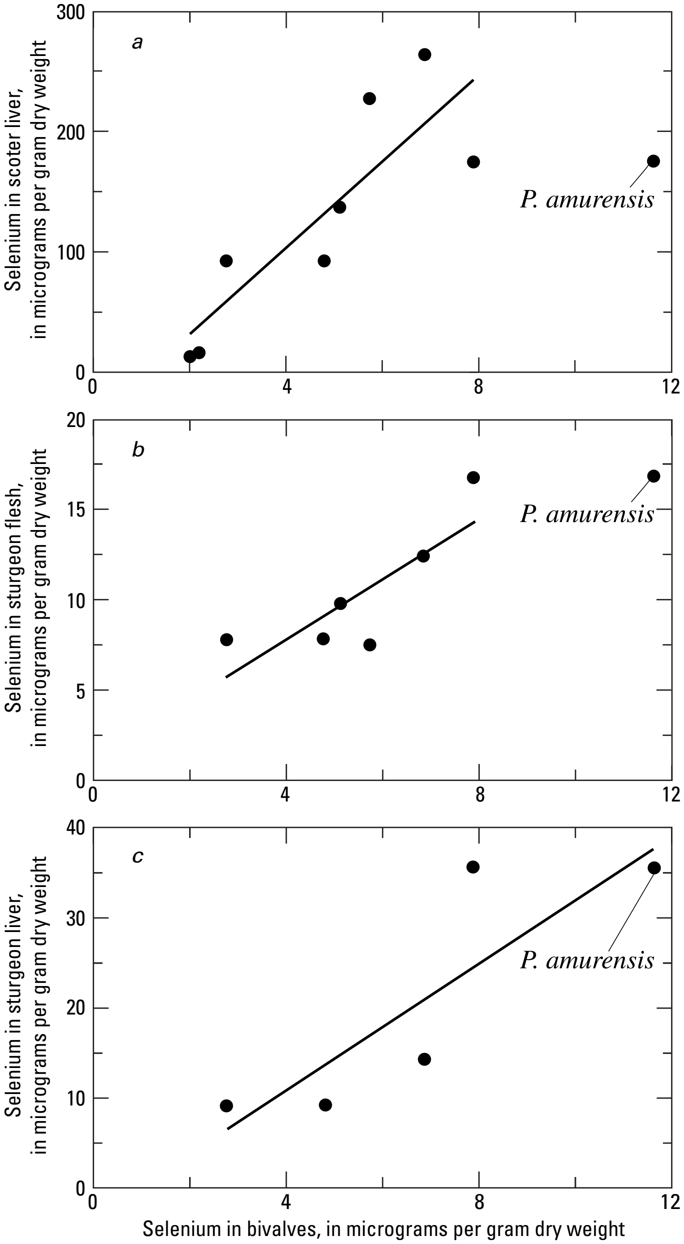

Figure 25. Observed selenium concentrations in (*a*) surf scoter liver, (*b*) white sturgeon flesh, and (*c*) white sturgeon liver as a function of bivalve selenium concentrations. (Data from California Department of Fish and Game Selenium Verification Study, White and others, 1987; 1988; 1989; Urquhart and Regalado, 1991).

Table 30. Regression and curve-fit data (correlation coefficient, slope, and y-intercept) for two species of bivalve and three bivalve predators.

[Data sources: White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991; Johns and others, 1988; Linville and others, 2002.]

Average selenium (µg/g dry weight)						
Bivalves	**Surf scoter (flesh)**	**Surf scoter (liver)**	**Greater or lesser scaup (flesh)**	**Greater or lesser scaup (liver)**	**White sturgeon (flesh)**	**White sturgeon (liver)**
Bivalves = *Corbicula fluminea*						
4.8	12.5	92.8	7.1	25.8	7.81	9.20
2.77	12.5	92.8	7.1	25.8	7.81	9.20
2.2	4.0	15.5	3.9	9.7	–	–
5.13	21.3	137	12.0	29.1	9.84	–
2.01	3.0	12.5	6.57	13.57	–	–
5.73	37.8	228	23.93	65.12	7.47	–
6.87	51.8	263	–	–	12.38	14.19
7.90	35.8	174	–	–	16.81	35.50
Correlation	$R^2 = 0.77$	$R^2 = 0.74$	$R^2 = 0.59$	$R^2 = 0.64$	$R^2 = 0.66$	$R^2 = 0.62$
Slope	7.12	36.06	3.42	9.63	1.68	4.33
Intercept	–10.98	–41.57	-2.80	-8.14	1.04	–7.15
Bivalves = *Potamocorbula amurensis*						
4.8	–	92.8	–	–	–	9.2
2.77	–	92.8	–	–	–	9.2
2.20	–	15.5	–	–	–	–
5.13	–	137	–	–	–	–
2.01	–	12.5	–	–	–	–
6.87	–	–	–	–	–	14.19
11.63	–	228	–	–	–	35.5
11.63	–	263	–	–	–	–
11.63	–	174	–	–	–	–
Correlation	–	$R^2 = 0.86$	–	–	–	$R^2 = 0.91$
Slope	–	19.28	–	–	–	3.15
Intercept	–	–2.35	–	–	–	–3.50

have the ecological effect of replacing the selenium load scheduled for removal through treatment by oil refiners by 1998.

Ecological Risk

Cumulative Effects on the Bay-Delta

Some uncertainty characterizes transformations and other aspects of the analysis given above. However, enough is known about the biogeochemistry and biotransfer of selenium that, using multiple lines of evidence, relevant conditions and outcomes can be bracketed for the Bay-Delta. It is useful to consider four levels of certainty when developing a statement of risk for selenium:

- The greatest certainty occurs if waterborne, particulate, bioaccumulation, and predator lines of evidence are accompanied by direct observations of toxicity, 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 effects are available.
- Moderate certainty results if more than one line of evidence from a chain of evidence is available.

Table 31. Data employed in regression of bivalve selenium concentrations and bivalve predator selenium concentrations.

[Means from different years are aggregated. Bivalves are from different species (*Corbicula fluminea; Mya arenaria; Macoma balthica*; and *Potamocorbula amurensis*) and different studies (White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991; Johns and others, 1988; Linville and others, 2002).]

	Average selenium (µg/g dry weight)						
Date	**Bivalves**	**Surf scoter (flesh)**	**Surf scoter (liver)**	**Greater or lesser scaup (flesh)**	**Greater or lesser scaup (liver)**	**White sturgeon (flesh)**	**White sturgeon (liver)**
North Bay (Suisun Bay and San Pablo Bay)							
1986	4.8	12.5	92.8	7.1	25.8	7.81	9.20
1987	5.13	21.3	137	12.0	29.1	9.84	–
1988	5.73	37.8	228	23.9	65.1	7.47	–
1989	6.9	51.8	264	–	–	12.4	14.2
1990	7.9	35.8	174	–	–	16.8	35.5
1995–96	11.6	35.8	174	–	–	16.8	35.5
Humboldt Bay							
1986	2.2	4.0	15.5	3.9	9.7	–	–
1988	2.0	3.0	12.5	6.57	13.6	–	–

Table 32. Measured selenium concentrations in clams (*C. fluminea*, 1988 to 1990; *P. amurensis*, 1995 to 1996), scoter, scaup, and sturgeon (1988 to 1990); and a summary of forecasts of selenium concentrations in a generic bivalve, scoter, scaup, and sturgeon at the head of the estuary under two projected selenium load scenarios, identified speciation/transformation regimes, and bivalve assimilation efficiencies (AE's) for the low flow season of a critically dry year.

[Forecasted predator liver concentrations are predicted by extrapolation from regressions between bivalve and predator concentrations using data from 1986 to 1990 (tables 30 and 31). C1 = K_d of $1{\times}10^4$, typical of suspended sediment; C2 = K_d of 3×10^3, typical of shallow-water bed sediment; and C3 = K_d of 1×10^3, typical of inefficient transformation. AE1 = 0.35; AE2 = 0.55; and AE3 = 0.63]

	Critically dry year, low flow season			
Scenario or date	**Bivalve selenium (µg/g dry weight)**	**Surf scoter liver selenium (µg/g dry weight)**	**Greater or lesser scaup liver selenium (µg/g dry weight)**	**White sturgeon liver selenium (µg/g dry weight)**
San Luis Drain extension load of 18,700 lbs per six months				
Inefficient transformation: C3 and AE1	15	248	136	45
Shallow sediment: C2 and AE2	70	1,293	664	221
Suspended sediment: C1 and AE3	266	5,017	2,546	848
San Joaquin River targeted load of 3,400 lbs per six months				
Inefficient transformation: C3 and AE1	2.5	10	16	5
Shallow sediment: C2 and AE2	11.8	187	105	35
Suspended sediment: C1 and AE3	45	818	424	141
Measured in North Bay (average)				
1988–90	8 (*Corbicula fluminea*)	164	64	30
1995–96	12 (*Potamocorbula amurensis*)	–	–	–

- Low certainty results if a risk evaluation is based on one line of evidence.

The scenarios, model, and forecasts demonstrate that many of the most likely combinations of load, hydrology, climate, transformation, and bioavailability pose a significant ecological risk to the Bay-Delta. In general, San Luis Drain discharges that would meet demands for drainage pose risks to fish and bird reproduction and the risk of fish extinction as a result of contamination of their invertebrate food. If biogeochemical conditions like those currently in the Bay-Delta predominate during projected selenium 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 selenium undergoes reactions typical of low flow or longer residence times, highly problematic bioaccumulation is forecast to result. There are some conceivable scenarios of increased selenium discharge to the Bay-Delta where the potential of risk is reduced, such as in a *targeted* load scenario for the San Joaquin River, but only if particulate transformation and assimilation are inefficient during low flow seasons. Those conditions are of low likelihood in that such inefficient particulate and suspended matter reactions are not typical of the Bay-Delta. Discharge of selenium from the San Joaquin Valley would be predominantly selenate, rather than the selenite released by refineries prior to 1998. Transformation of selenate to particulate selenium is observed throughout nature where residence times are extended. The efficiency of this transformation and the resulting particulate selenium concentrations are key to forecasting selenium bioaccumulation and effects.

Dry year and wet year, low flow season

Critically dry years and low flow seasons will determine the ecological effects of selenium. 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 critically dry year (table 33 and fig. 26) shows forecasted selenium concentrations for each media (water, sediment, invertebrate, predator) employed in the Bay-Delta selenium model, along with concern levels (see previous discussion; tables 13, 14, and 15). The forecasts are for the head of the estuary for a range of selenium loads (6,800; 18,700; or 44,880 lbs released per six months) discharged from a proposed San Luis Drain extension. The assumed conditions are a particulate speciation/transformation regime indicative of shallow-water sediment (C2, 3×10^3) and a moderate generic bivalve assimilation efficiency (AE2, 0.56) to reflect bioaccumulation potential. In general, forecasted waterborne, particulate, dietary, and predator tissue selenium concentrations exceed illustrated guidelines in every forecast considered, where the input is from a proposed San Luis Drain extension (table 33 and fig. 26). In these critically dry year/low flow season forecasts, a 40 µg/g dietary extinction guideline also is exceeded in all forecasted bivalve (food) concentrations except that bivalve concentration forecasted at the lowest load considered (6,800 lbs per six months). However, that concentration in prey (28 µg/g) results in concentrations in liver tissue of white sturgeon and greater and lesser scaup that exceed the adverse effects tissue guideline range (10–18 µg/g) in liver.

If a San Luis Drain extension discharges selenium 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 selenium to the Bay-Delta through the San Joaquin River (for example at 3,500 lbs per six months), the risks are less than for those forecasted for a discharge through a San Luis Drain extension. However, for the low flow season of a dry year, selenium concentrations in prey and predators are forecasted that are similar to selenium concentrations observed (and forecasted) during conditions in the Bay-Delta prior to refinery cleanup. During this time, forecasted selenium concentrations for both prey (food) and predator tissue exceed concentration with a high certainty of producing adverse effects. Thus, selenium from the San Joaquin Valley replaces, in terms of food web exposure and effects, the selenium 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 to trigger human health advisories.

Illustrated low-flow season scenarios where risks to benthic predators is somewhat reduced are found in five forecasts, but only if:

- during both wet and critically dry years, a proposed San Luis Drain discharge is 150 ft^3/s (half the capacity), the drainage is treated to attain a selenium concentration of 50 µg/L (6,800 lbs per six months), and selenium transformation and assimilation in the Bay-Delta is inefficient (C3/AE1); or

- during a wet year, the San Joaquin River discharges 3,500 lbs per six months and selenium transformation and assimilation are inefficient (C3/AE1) or indicative of shallow-water sediments (C2/AE2); or

- during a dry year, the San Joaquin River discharges 3,500 lbs per six months and selenium transformation and assimilation are the least inefficient found in any of the receiving waters studied previously (C3/AE1).

The necessary inefficient transformation is unprecedented in the Bay-Delta during low flows, so these seem unlikely scenarios.

Wet year, low and high flow seasons

High flow conditions afford some protection under certain forecast conditions. Under these conditions, poten-

Table 33. Risk guidelines and cumulative summary of forecasts of selenium concentrations in water, particulate material, a generic bivalve, scaup, and sturgeon at the head of the estuary historically and under projected selenium load scenarios, identified speciation/transformation regimes, and bivalve assimilation efficiencies (AE's) for the low flow season of a critically dry year.

[Forecasted predator liver concentrations are predicted by extrapolation from regressions between bivalve and predator concentrations using data from 1986 to 1990 (tables 30 and 31). C2 = K_d of 3 × 10^3, typical of shallow-water bed sediment. AE2 = 0.55]

Critically dry year, low flow season					
Selenium					
Load (lbs per six months)	**Composite freshwater endmember (µg/L)**	**Particulate (µg/g dry weight) C2 = K_d of 3×10^3**	**Bivalve (µg/g dry weight) AE2 = 0.55**	**White sturgeon liver (µg/g dry weight)**	**Greater and lesser scaup liver (µg/g dry weight)**
San Luis Drain extension					
6,800	2.1	6.2	28	87	261
18,700	5.1	15	70	221	664
44,880	12	36	163	519	1,557
San Joaquin River, *targeted* load					
3,500	0.86	2.6	11.8	35	105
Conditions prior to refinery cleanup					
–	0.53	1.6	11	30	65
Guidelines (concern)[a]					
–	1–5	0.4–1.5	2–5	12–15	10–18

[a] Guidelines may not be, individually, realistic indicators of risk, but are used here as reference points for context (see discussion in text and tables 13, 14, and 15).

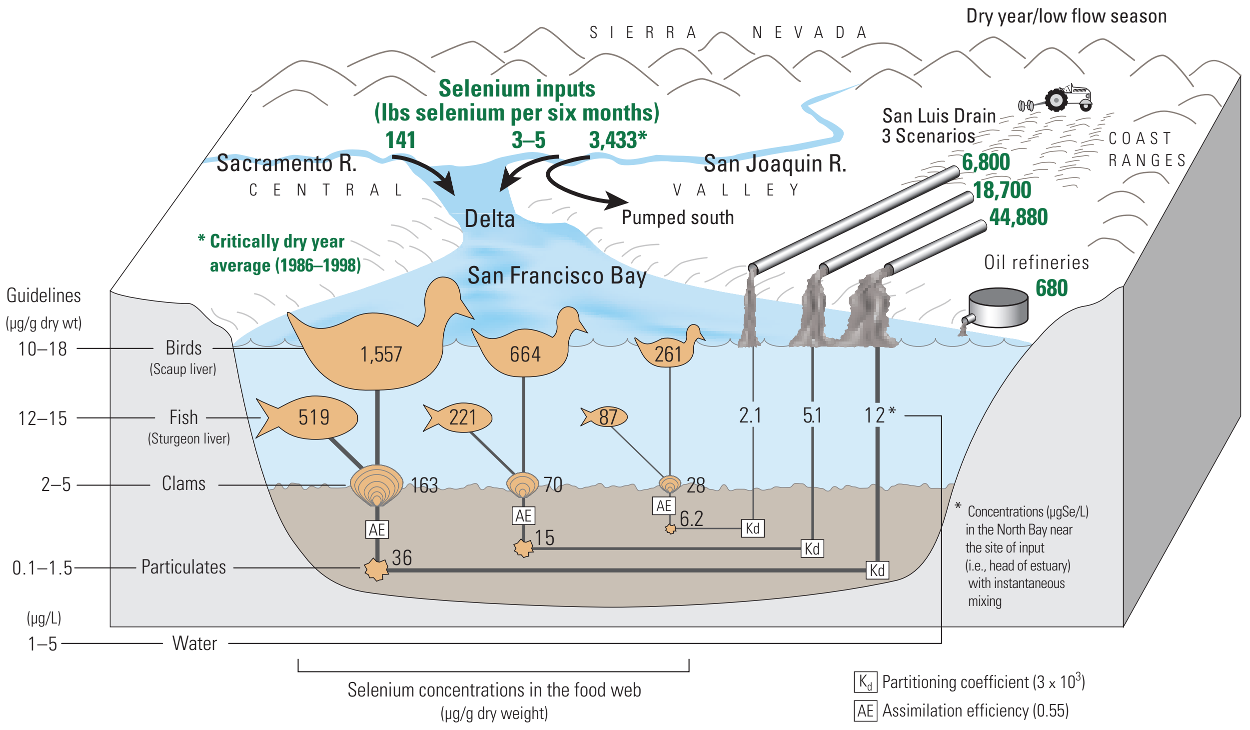

Figure 26. Schematic representation of forecasts of selenium concentrations in water, suspended material, a generic bivalve, and predators at the head of the estuary under three projected selenium load scenarios (lbs per six months) for a San Luis Drain extension directly to the Bay-Delta for a critically dry year during the low flow season. [Other assumptions: (1) refinery input, 680 lbs per six months; (2) speciation/transformation regime, K_d of 3,000; (3) bivalve assimilation efficiency, AE of 0.55.]

tial of risk can be reduced in wet years during high flows at selenium loads of 6,800 lbs or 18,700 lbs discharged through a San Luis Drain extension or 3,500 lbs discharged through the San Joaquin River per six months where transformations are those of shallow-water sediment or are inefficient (C2/AE2 and C3/AE1). During wet years and low flows, selenium concentrations in prey remain at <10 µg/g only at the inefficient transformation (C3). During the San Joaquin River selenium load scenario, higher transformation and assimilations (C1/AE3 or AE4) also result in prey of <10 µg/g, but not at San Luis Drain loads of 6,800 lbs or greater per six months.

If concentrations in the San Joaquin River are regulated under a concentration management plan, increased San Joaquin River inflows will result in increased selenium 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 San Joaquin River (fig. 18). Higher concentrations result because the higher selenium 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 selenium 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 and others, 1979, 1985; Nichols and others, 1986; Peterson and others, 1989). Also during high inflows, highly contaminated particulate material from the San Joaquin River and/or a San Luis Drain extension is most likely to add to the selenium load in the estuary.

Implications for Water Quality Criteria for the Protection of Aquatic Life

In many forecasts, the considered load scenario results in selenium concentrations in prey and predators that equal or exceed selenium concentrations forecasted and measured in the Bay-Delta prior to refinery cleanup In some forecasts, selenium concentrations in the Bay-Delta remained below the 2 µg/L water quality criterion recommended for the protection of aquatic life (USFWS and NMFS, 1997 and amended 2000), but those predators using the specific bioaccumulation pathway from sediment and benthic/suspended biomass to bivalves were, nevertheless, affected. Forecasts described here suggest that even at waterborne selenium concentrations at the head of the estuary of 1 µg/L, all risk of adverse effects cannot be eliminated.

Conclusions

Extent and Sustainability of Agricultural Discharge from the San Joaquin Valley

Taking a broad view, two lines of evidence are used here to show the general magnitude of the accumulated selenium reservoir in the western San Joaquin Valley. Calculations at the lower range of projections show that a long-term reduction in selenium discharge would not be expected for 63 to 304 years, if selenium is disposed of at a rate of about 42,500 lbs per year. Drainage of wastewaters outside of the San Joaquin Valley may slow the degradation of San Joaquin Valley resources, but drainage alone cannot alleviate the salt and selenium build-up in the San Joaquin Valley, at least within a century, even if no further inputs of selenium from the Coast Ranges occur. The amounts of ground water, salt, and selenium that have accumulated in the internal reservoir of the San Joaquin Valley may make it impractical to limit management to an annual imbalance (where input is greater than output) because of comprehensive effects to soils, aquifers and wildlife habitats.

However, forecasts of annual San Joaquin Valley agricultural discharges provide a basis for determining the upper and lower limits of selenium discharge from the western San Joaquin Valley (tables 6 to 9; 17). Secondarily, the projections provide the basis for determining the magnitude of selenium load reductions that may become necessary to achieve a specific *targeted* selenium load for environmental or restoration *targets* or objectives.

Agricultural inputs or discharges in the analysis presented here are divided into three groups depending on management scenarios to narrow the range of possibilities:

1. **Supply-driven management.** A range of 3,000 to 8,000 lbs selenium per year is assumed to address an environmental protection priority through a *targeted* load that cannot be exceeded. The basis for this scenario stems from:

    a. WY 1997 to 2001 load limits for the Grassland subarea are from 5,661 to 6,660 lbs selenium per year for discharge through the San Joaquin River. Grassland subarea loads modeled for the river as part of TMDL regulation to meet the 5 µg/L concentration objective in the San Joaquin River 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; appendix C).

    b. The Westlands subarea load estimated as part of evidentiary hearings is 8,160 lbs selenium per year (assuming 200,000 affected acres; drainage generation of 0.3 acre-ft per acre per year; and a selenium concentration of 50 µg/L) (table 7). Thus, a load of 8,000 lbs selenium per year may be a lower limit of discharge through a proposed San Luis Drain extension.

2. **Demand-driven load with management of land and/or drainage quality.** A range of 15,000 to 45,000 lbs selenium per year is assumed to address agricultural needs, to some degree, for draining saline or waterlogged soils. In this scenario, the quality and quantity of drainage are controlled by managing volume per acre and/or quality of the drainage. A range of loads (19,584 to 42,704 lbs selenium per year) is projected using a selenium concentration of 50 µg/L selenium (controlled concentration) and the amount of *problem water* or subsurface drainage with implementation of a management plan (demand driven volume) (table 6).

3. **Demand-driven load with minimum management.** A range of 45,000 to 128,000 lbs per year is 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 this scenario, a range of loads (42,704 to 128,112 lbs selenium per year) is projected using a selenium concentration of 150 µg/L (non-controlled concentration) and the amount of *problem water* defined by the Drainage Program for year 2000 without implementation of a management plan (demand driven volume) (table 6).

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

Water Management Implications

Implications for water management found through use of a range of selenium load scenarios and the comprehensive approach illustrated in the Bay-Delta selenium model are:

- The most significant effects 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 selenium effects must take the influences of variable river inflows into account.

- Selenium effects in the Bay-Delta also could increase if water diversions increase or if San Joaquin River inflows increase with concomitant real-time discharge of selenium that increases selenium loading (the selenium issue and the water management issues are tightly linked).

- Construction of an extension of the San Luis Drain would increase selenium 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 San Luis Drain 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 effect of a San Luis Drain extension.

- Treatment also may be important in determining source loads effects. 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 selenium in the influent, but result in enhanced selenium food chain concentrations if speciation in the effluent changes to increase the efficiency of uptake.

Low flow conditions are considered here as the critical time (the ecological bottleneck) that will determine the effects of selenium 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 selenium are probably near their maxima when migratory species leave the estuary, enhancing risk of biological damage. Animals that will be most vulnerable to selenium effects probably include those that feed on benthos such as bivalves and those that are active (preparing for reproduction or for which early life stages develop) in the estuary in September through March.

If water quality criteria are to be used in managing selenium inputs, the composite freshwater selenium 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 selenium concentration that is the starting point for determining the exposure that Bay-Delta organisms will experience.

Indicators of Ecological Risk and Monitoring Needs

Various protective guidelines and criteria are employed in this report as reference points. These may not be, individually, realistic indications of ecological risk. For example, in the Bay-Delta neither the USEPA criterion of 5 µg/L selenium nor the recommended USFWS criterion level of 2 µg/L alone, would be sufficient to protect the estuary if selenium transformations to particulate concentrations are efficient. The most effective interpretation and determination of risk includes use of monitoring data and development of guidelines for all critical media. Used in-combination, such data and criteria might be the most useful way to manage selenium in an ecosystem. Hence, the need for systematic long-term monitoring that includes all food web components is crucial to protection of ecosystems receiving selenium discharges. The linked components (water, particulate material, food, and predator tissue) and processes (speciation, transformation to particulate forms, bioaccumulation, and trophic transfer to predators) addressed here provide the necessary framework for a feasible approach for site-specific monitoring and analysis.

Monitoring, as conceptualized below, would sample critical environmental components at a frequency relevant to each process to determine the impacts of management changes, trends in selenium contamination, and changes in reactions that determine fate and effects of selenium. A linked or combined approach would include all considerations that cause systems to respond differently to selenium contamination.

1. In any site-specific analysis of selenium impacts, it is important that "site" be defined by all hydrologically relevant components. Hydrologic models would serve as a basis for developing this infrastructure. Specifically, the Bay-Delta ecosystem is connected to the San Joaquin River ecosystem. The Delta is the transition zone between the Bay and the largest potential source of selenium (i.e., agricultural drainage from the San Joaquin Valley via either a dedicated conveyance or the San Joaquin River).

2. The vulnerability of downstream water bodies should be considered when evaluating of upstream source waters. Toxicity problems may not appear equally in all "site" components because some components may be more sensitive than others. For example, the San Joaquin River, as a flowing water system may be less sensitive to selenium 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.

3. Any analysis of selenium effects must take the influences of variable river inflows into account. Selenium impacts in the Bay-Delta could increase if water diversions increase or if San Joaquin River inflows increase with concomitant increases in selenium loading (i.e. the selenium issue and the water management issues are tightly linked). 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, with critically dry years comprising 15 of those years.

4. A mass balance or budget of selenium through the estuary is crucial because internal (oil refinery) and external (agricultural drainage) sources of selenium are changing as a result of management. At a minimum, a mechanism for tracking selenium loading via oil refineries and the San Joaquin River is needed based on San Joaquin River, Sacramento River, and Bay-Delta hydrodynamics. Monitoring programs need to measure the ongoing status of the system in terms of inputs, storage in sediment, through-put south via the Delta-Mendota Canal and California Aqueduct, and through-put north to the Bay.

5. Storms and high-flow years will be times of increased regional discharge of San Joaquin Valley drainage containing high concentrations and loads of selenium. If the precipitation-dependence of agricultural selenium inflows is not recognized, violations of upstream water quality criteria and load targets could result on a recurring basis. 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.

6. Multiple-media guidelines, in combination, provide a feasible reference point for monitoring. 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; concentrations of dissolved selenium and suspended selenium; selenium speciation in water and sediment; assimilation capacities of indicator food chain organisms; and selenium concentrations in tissues of prey and predator species. Determination of transformation efficiency and processes that determine K_d's (distribution or partitioning coefficients) of selenium in the Bay-Delta and San Joaquin River 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.

7. Invertebrates may be the optimal indicator to use in monitoring selenium because they are practical to sample and are most closely linked to predator exposure. Knowledge of optimal indicators in the Bay-Delta and San Joaquin River are necessary to fully explore feeding relations. Resultant correlations with selenium bioaccumulation in food webs are a part of this process.

8. Determination of food web inter-relations would help identify the most vulnerable species. Specific protocols that include life cycles of vulnerable predators including migratory and mobile species would then document selenium effects for the species most threatened.

9. If management and regulatory measures to restore the San Joaquin River ecological resources to their former level of abundance are to be effective, then the biogeochemistry of selenium, ecological processes, and hydrodynamics in this system must be further investigated and understood. Adaptive management and monitoring for the San Joaquin River should be based on the biotransfer of selenium and consider the environmental stresses imposed by present degraded conditions. Current discharge of agricultural drainage to the San Joaquin River via a 28-mile section of the San Luis Drain is under monthly and yearly load limitations. To determine whether load manipulation actually protects vulnerable predators, the following monitoring plan components are needed:

    a. identification of vulnerable food webs;

   b. identification of sites most at risk from impacts of agricultural drainage;
   c. analysis of effects on predators that includes food web components;
   d. identification of elevated risk periods for effects based on hydrodynamics; and
   e. calculation of protective loads/concentrations based on bioaccumulation in prey.

10. In view of the analysis of the existing selenium reservoir in the San Joaquin Valley, consideration of the degradation of groundwater aquifers 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 selenium.

11. Treatment also may be important in determining source load 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 selenium in the influent, but result in enhanced selenium food chain concentrations if speciation in the effluent changes to increase the efficiency of uptake.

Concluding Perspective

Demonstrated and validated here is a methodology that uses existing knowledge of each considered factor in a sequence of linked processes that control the ecological effects of selenium. These linked processes are then incorporated into an internally consistent evaluation using multiple lines of evidence. Any future analysis of effects from selenium discharged to the Bay-Delta through a proposed San Luis Drain extension needs to be at least as complete and could profitably build from the framework presented here.

This new tool, the Bay-Delta selenium model (fig. 2), is employed to generate site-specific forecasts of selenium concentrations and effects based on loads, prey, and predators. It is concluded here that protective criteria be biologically based and consider (1) vulnerable food webs and elevated risk periods; (2) speciation and contaminant concentrations in sources such as particulate material that most influence bioavailability; (3) bioaccumulation or biodynamic models that help integrate exposure; and (4) multiple media concentrations (water, particulate material, and tissue of prey and predators) that, in-combination, determine risk or hazard. In the Bay-Delta, bivalves appear to be the most sensitive indicator of selenium contamination.

Appendices A to F

Appendix A. Export Drain Planning History and Geologic Inventory

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Envisioned Drainage Discharges and Salt Loads

Planning

The San Luis Unit (fig. A1) in the western San Joaquin Valley encompasses over 700,000 acres in the Westlands, Panoche, Broadview, Pacheco, and San Luis Water Districts of the Grassland and Westlands subareas (USBR, 1981). Agricultural development and irrigation has continued on these lands despite salinized soils, with an attendant increase in areas that require drainage. Limiting factors include soil, topography, and drainage.

Starting in 1954, land in the San Luis Unit was classified as to suitability for crop production and management cost (USBR, 1978; Ogden, 1988). Land was rated based on presence of alkali (salt), hardpan (impeded drainage), and roughness (uneven land surface). A large segment of *Class 3* land (that is, land known to require difficult and costly management) was identified adjacent to the valley trough. By 1962, 12 percent of the San Luis Unit was comprised of *Class 4* land (that is, land known to have a reduced payment capacity for irrigation and/or drainage improvements based on agricultural return). *Class 4* land mainly was identified in areas directly affected by erosion from the Coast Ranges to the west (USBR, 1978). Agriculture continues to expand into *Class 4* land, even though this expansion is controversial. These areas require the most capital for drainage removal, but have the least ability to pay for drainage improvements. As recently as 1997, the USBR petitioned to expand the *place of use* of Central Valley Project water supplies into areas of the San Luis Unit that never before have received federal water supplies (State Board, 1997).

Historic estimates of drainage needs (that is, envisioned rates of flow or volume of drainage necessary to lower the water table) provide an interesting context for modern estimates. Of general note is that, even though amounts of drainage for conveyance out of the San Joaquin Valley have increased since planning began in 1955, the design capacity of the main component of a drainage facility has remained relatively unchanged through time (300 ft^3/s). Estimates do vary, however, for the rate of flow for the north and south ends of the drain (100 ft^3/s in the south and 450 ft^3/s in the north).

Consideration and assessment of hydrologic balance in a subarea also gives insight into expected drainage requirements. In a 1988 analysis (CH2M HILL, 1988), the Northern and Grassland subareas were considered in hydrologic equilibrium, which implies little future change in the extent of land that need drainage. A distinction was made in the analysis between managing the accumulated hydrologic imbalance (area of drainage affected land) and managing the annual imbalance (rate of water table rise). 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, salt, and selenium. Achieving hydrologic balance also would not achieve salt balance. Salts would continue to accumulate in the soils and aquifers of the San Joaquin Valley.

In addition to estimates of flow and volume, planning documentation gave estimates of water quality (based on total dissolved solids or specific conductance) to enable calculation of expected loads of salt (tons per year). The amount of salt projected for discharge from the San Joaquin Valley, as a whole, helps determine the magnitude of salt build-up. Differences in the amounts of salt discharged per subarea helps distinguish differences due to geology and hydrology in the affected areas. Selenium analyses on which to base calculation of selenium loads were not available until the mid-1980s (Presser and Ohlendorf, 1987).

Export of both salt and nitrate (7,604 tons of nitrate [NO_3 + NO_2 (N)] calculated for a worst case scenario for 2020) were considered problematic for receiving waters (USBR, 1978; Interagency Drainage Program, 1979a, b). Salt would aggravate problems of salinity intrusion into the Delta thereby interfering with beneficial uses of Delta waters. Nitrates would disturb the balance of nutrient levels in the estuary, thereby causing eutrophication and elevated turbidity. Limited data on toxicity and constituents of concern (such as, nitrate, phosphate, pesticides, dissolved oxygen, boron, arsenic, heavy metals) in drainwater are listed in historical reports (Department of Water Resources, 1965a; Interagency Drainage Program, 1979a, b; Brown and Caldwell, 1986; USBR, 1984b through h), but are not considered further here.

Compiled here are examples of the many sets of data for drainage volume and drained acreage that existed throughout the planning history for a drain to export agricultural drainage from the San Joaquin Valley; however, the review presented here is by no means exhaustive. References are mainly documentation by or for Federal agencies and joint Federal and State efforts (such as Hydroscience, 1977; USBR, 1978; Interagency Drainage Program, 1979a; CH2M HILL, 1985; Drainage Program, 1990a; USBR, 1992; Drainage Implementation Program, 1998). A parallel set of reports that document early State planning efforts are not as extensively cited (see, for example, Department of Water Resources, 1965a, b, 1969, 1974, 1978; State Board, 1979). Many documents contain similar estimates (or reference the same data) based on generalized data for future conditions. For example, studies in 1979 and 1990 both state concern over 400,000 acres of affected farmland that needs drainage due to a high water table (Interagency Drainage Program, 1979a; Drainage Program, 1990a). Evaluations of alternative disposal areas, which show engineering aspects and the net revenue disposal benefit of different drainage conveyances, mainly address management aspects, not source loads estimates (see, for example, USBR, 1955, 1962; Department of Water Resources, 1965a; Interagency Drainage Program, 1979b; Brown and Caldwell, 1986).

Specific Estimates

From 1975 to 1977, both the Interagency Drainage Program and the USBR prepared estimates of discharge from the San Luis Unit (USBR, 1978). The 1970's planners envisioned an agricultural drainage canal with a design capacity of

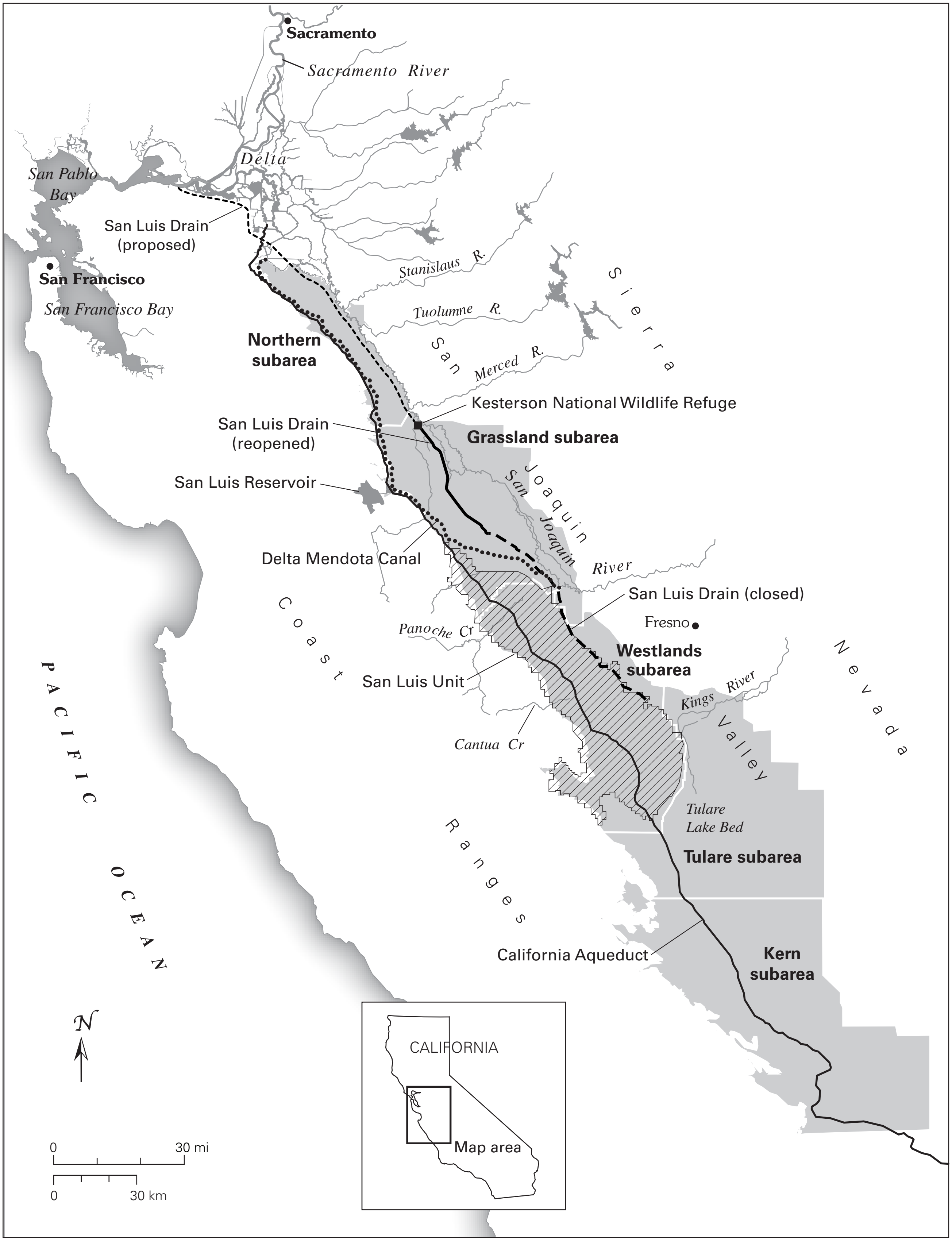


Figure A1. Map of San Luis Unit of the Central Valley Project, California.

300 ft^3/s and a length of 197 miles. Estimates of quantity were calculated through the year 2080 (approximately 100 years into the future) and of quality through the year 2030 (table A1). Maximum quantities of drainage originally were not anticipated for *at least another 100 years* in the original plan, but revised estimates showed the *ultimate (maximum) quantity* of drainage would be available by 2030 (table A1). A hydrologic schematic of *Ultimate Waterflow Conditions* developed for the San Luis Unit shows a drain discharge of 144,200 acre-ft per year from 300,000 acres underlain by subsurface drains (fig. A2). The historic numerical model simulations were based on salinity measurements. The model predicted that the discharge of the poorest quality of drainage would occur during early years of irrigation and drainage. Annual discharge of salt from the San Luis Unit would increase from 43,710 tons per year to a maximum of 1.5 million tons per year after 40 years of discharge (USBR, 1978). As *equilibrium conditions* between soil and water were approached, concentrations of dissolved minerals in the drainage water were expected to decrease. The model also predicted salt concentrations (mg/L total dissolved solids, TDS) would decrease by 50 percent after 40 years of drainage.

In 1979, a final report was prepared by the Interagency Drainage Program recommending completion of a valleywide drain to service five areas (North, Delta-Mendota, San Luis, Tulare Lake, and Kern County) and to discharge into the Bay-Delta at Chipps Island. The report also included a first stage environmental impact report (Interagency Drainage Program, 1979a, b). Estimates of expected annual quantities of drainage ranged from 57,000 acre-ft in 1985 to 668,000 acre-ft in 2085, when drained acres were expected to reach over one million acres. Loads of salt requiring disposal were estimated to range from 3.1 to 3.9 million tons per year for a valleywide drain.

In 1983, the USBR estimated drainage quantity and quality (concentration of salt, seven major elements, and twelve minor elements, but selenium was absent) for expected discharge from the San Luis Unit during the period 1995 to 2095 (USBR, 1983) (fig. A3). Water-quality projections were based on concentration averages in the San Luis Drain for the period September 1982 to January 1983 (USBR, 1983), before the discovery of deformities at Kesterson National Wildlife Refuge. Estimates of drainage volume ranged from 84,525 acre-ft in 1995 to 274,270 acre-ft in 2095 for the combined discharge from the San Luis Service Area (equivalent to Westlands Water District; 48,885 to 192,105 acre-ft) and the Delta-Mendota Service Area (encompassing Grassland subarea and other northern water districts; 35,660 to 82,158 acre-ft). A steady rise in discharge was predicted from 1995 to about year 2035 when the rate of increase slows, but continues rising through the projected year 2095 (fig. A3). The worst-case scenario was to occur in year 2020 when 1.8 million tons per year of salt was to be discharged in 201,025 acre-ft of drainage.

In 1988, salt and water inflows and outflows to the San Joaquin Valley were conceptualized (CH2M HILL, 1988) (fig. A4). Calculations specific to five subareas determined the annual groundwater and salt accumulation. Results of these studies showed volumes of water and tons of salt recharged or discharged by specific processes (such as evapotranspiration), sources (such as canal imports), or reservoirs (such as confined aquifers). The annual salt accumulation determined for 1988 in the semi-confined aquifer of the valley for all five subareas was 3.3 million tons per year. The annual accumulation per subarea ranged from 1,000 tons per year to 1.5 million tons per year, due to differing hydrology, geology, and drainage options (see later discussion). An analysis for the Westlands subarea showed 44 percent of the salt was from dissolution of salts internal to the San Joaquin Valley; 49 percent imported from outside sources including irrigation water; and 7 percent from other sources such as seepage. The predicted conditions in the Westlands subarea showed the largest proportion of internal salt to imported salt for the five subareas. Westlands subarea is the most impacted by Coast Range sources of selenium because of its location on the Panoche Creek alluvial fan (see later discussion; Presser and others, 1990; Presser, 1994b). For the Westlands subarea, importation of higher quality water would have a diminished effect compared to other subareas because of this large reservoir of salt. The Northern and Grassland subareas showed high proportions of

Table A1. Historical prediction of drainage from the San Luis Unit (San Luis Service Area and the Delta-Mendota Service Area).

[Both sets of data and estimates (Interagency Drainage Program (1975) and USBR (1977) are included within USBR (1978). Model annual loads of salt were verified by sampling and analyses of drainage waters (USBR, 1978). The ultimate or maximum condition is defined by the Interagency Drainage Program as drainage of 300,000 acres.]

Future year	Interagency Drainage Program drainage estimate (acre-ft/year)	USBR drainage estimate (acre-ft/year)	USBR modeled load (tons salt/year)
1980	20,000	3,100	43,710
1985	–	8,700	159,210
1990	47,000	19,000	317,300
2000	64,000	33,100	521,400
2010	71,000	107,400	1,385,460
2020	78,000	152,300	1,538,230
2030	88,000	154,100	1,094,110
2040	98,000	–	–
2050	107,000	–	–
2060	114,000	–	–
2070	122,000	–	–
2080	129,000	–	–
Ultimate	150,000	–	–

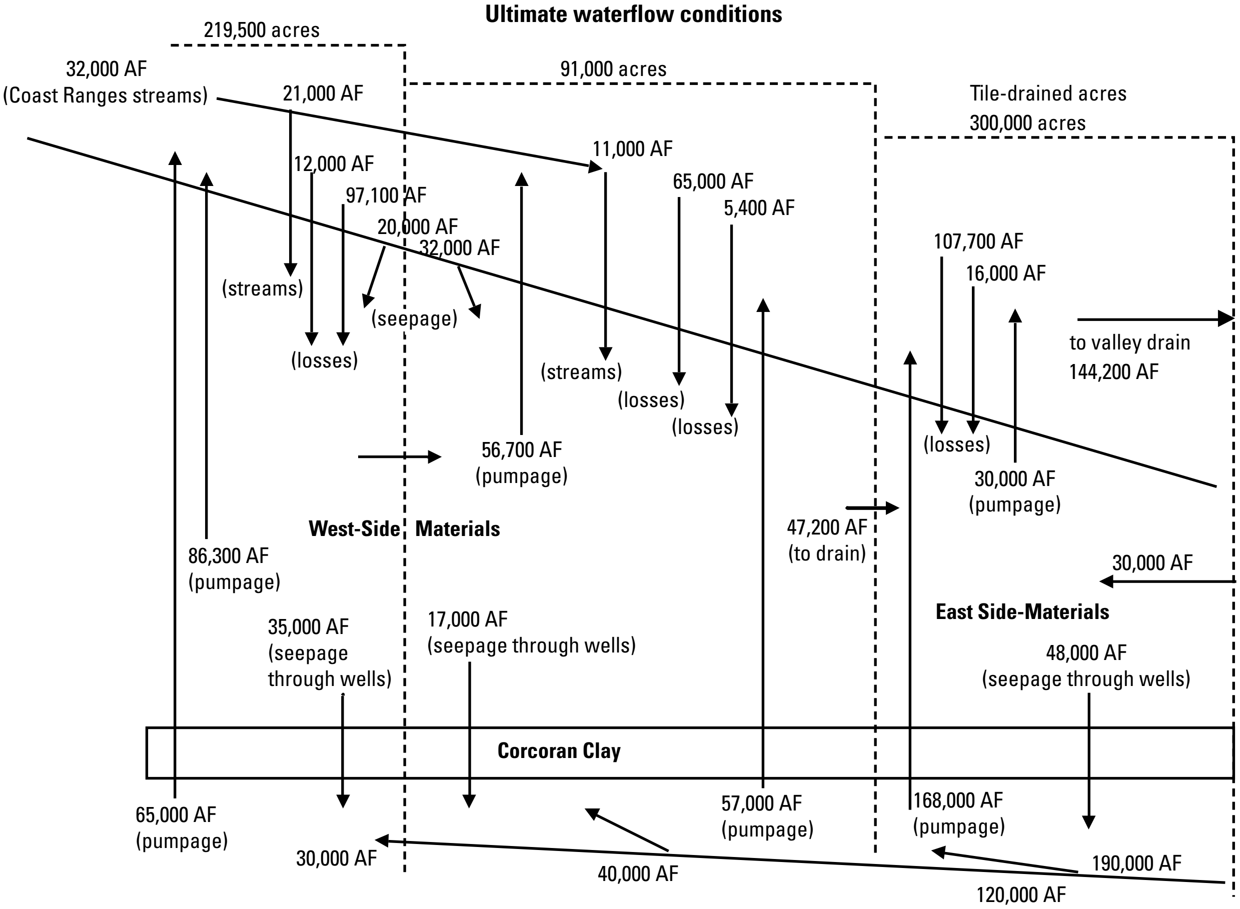


Figure A2. *Ultimate Waterflow Conditions* as known in 1978 of the San Luis Unit showing the 1) complexity of surface and ground water interactions; and 2) quantities of water influx and efflux [note prediction of 144,200 acre-ft (AF) for disposal in a valley drain] (adapted from USBR, 1978 Plate 2).

imported salt to internal salt and relatively low salt accumulations because of the availability of the San Joaquin River for salt discharge.

A 1989 analysis for the Drainage Program estimated that salt was accumulating at a rate of about 100,000 tons per year in the Grassland subarea (Drainage Program, 1989). On a recent detailed basis, calculations for the lower San Joaquin River basin, that includes the Grassland subarea and recycling to and from the San Joaquin River, show a doubling of salt within the basin every five years despite drainage to the San Joaquin River (net gain of 207,000 tons per year of a mean salt inflow of 917,000 tons per year) (Grober, 1996).

Re-evaluation in 1998 of salt importation data (neglecting salt reservoir calculations as done in 1988) showed an excess of salt inflow over outflow in all subareas (Drainage Implementation Program, 1998) (fig. A5; one railroad car is equivalent to 100 tons salt). The total annual imported salt was 1.5 million tons per year. This value does not include the calculated 620,000 tons per year discharged out of the valley through the San Joaquin River (Drainage Implementation Program, 1998). No data were given for internal salt or the status of subarea salt reservoirs.

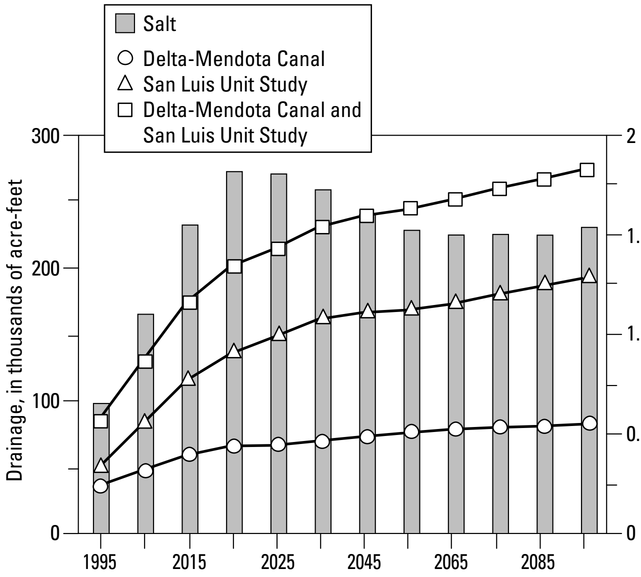


Figure A3. Expected salt loads and drainage volume from the San Luis Unit to the San Luis Drain during the period 1995 to 2095 (USBR, 1983).

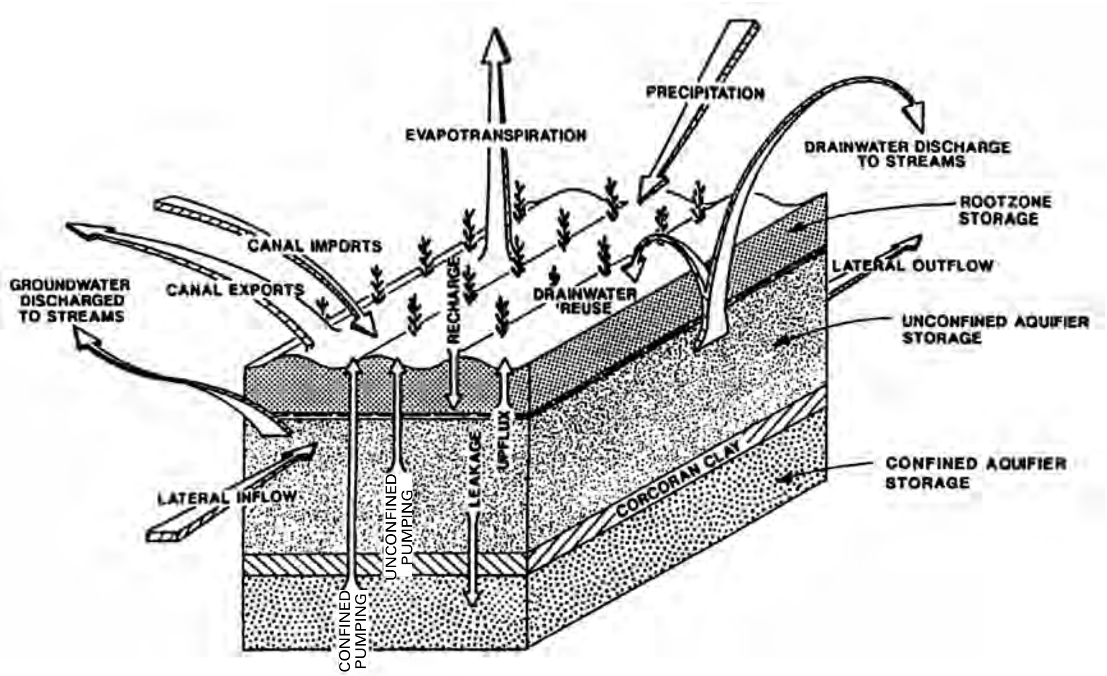


Figure A4. Conceptual water budget for the western San Joaquin Valley (adapted from USBR, 1989; and CH2M HILL, 1988).

Coincidentally, the input of 1.5 million tons per year of salt calculated as part of this 1998 re-evaluation also is the annual tonnage that was quoted in 1978 by the San Luis Task Force. The task force reviewed the management, organization, and operation of the San Luis Unit to determine the extent to which the San Luis Unit conformed to the purpose and intent of Public Law 86-488. The task force noted that planning documents looked 40 years into the future (1950 to 1990):

> *At about the 1990 level of agricultural development in the San Joaquin River Basin, slightly more than 1.5 million tons of new salt will be added annually to the valley from applied irrigation water (page 161).*

Implemented Management

Current implemented agricultural wastewater management plans for five subareas are:

- Northern (26,000 drained acres) and Grassland (51,000 drained acres) subareas discharge agricultural drainage to the San Joaquin River. A State permit has been in place since 1997 to regulate drainage from the Grassland subarea to the San Joaquin River through use of a portion of the San Luis Drain as a conveyance facility (Central Valley Board, 1998a). The reuse of a 28-mile section of the San Luis Drain has been renamed the Grassland Bypass Channel Project (USBR and San Luis Delta-Mendota Water Authority, 1995 and 2001; USBR and others, 1998 and ongoing).
- Westlands subarea (5,000 drained acres, alleviating salinization in 42,000 acres) has a *no discharge* policy, that is, storage of drainage in the underlying groundwater aquifer and use of agricultural water supplies and the aquifer for dilution. Some consider this a recycling program (Drainage Program, 1989), although it has temporal storage, displacement, and distribution components to it. Degradation of groundwater aquifers is expected to occur. Ground water with dissolved solids of greater than 2,500 mg/L is considered unsuitable for irrigation (Drainage Program, 1990a)
- Tulare (42,000 drained acres) and Kern (11,000 drained acres) subareas are internally drained basins that discharge to privately owned evaporation ponds. Discovery of bird deformities in 1987 through 1989 caused the State to call for closure of some ponds and operation of the remaining ponds under permits (State Board, 1996a). State permits have regulated evaporation pond discharges since 1993 with various areas of mitigation wetlands required (Central Valley Board, 1993, 1997, and 1998c). Many evaporation ponds have closed or are in the process of closure; remaining ponds have been modified to lessen bird use. Documentation in 1999 showed that the number of individual basins and pond operators decreased by about 60 percent, but surface area of ponds only decreased from 6,715 to 4,895 acres (Drainage Implementation Program, 1999d).

Figure A5. A representation of salt balance in the western San Joaquin Valley showing salt inflow (approximately 40 railroad cars per day) and outflow (approximately 17 railroad cars per day discharged from the Grassland subarea through the San Joaquin River) (printed with permission, Drainage Implementation Program, 1998).

Geologic Inventory and Reservoir of Selenium in the San Joaquin Valley

Selenium Geologic Inventory and Mass Balance

Sediments enriched in salts (and by inference, selenium) have been accumulating for 1.0 to 1.2 million years on the alluvial fans of the San Joaquin Valley (Bull, 1964; Deverel and Gallanthine, 1989; Gilliom and others, 1989; Andrei Sarna-Wojcicki, U.S. Geological Survey, Menlo Park, Calif., personal commun., July 23, 1998). Salt and other trace elements originate from marine sedimentary rocks of the California Coast Range (Presser and Ohlendorf, 1987; Presser and others,1990; Presser, 1994b). Figure A6 visually illustrates some of the characteristics of the geologic sources of selenium in the Coast Ranges; the processes or erosion and runoff occurring in the valley; irrigation and drainage systems; and potential reservoirs (selenium inventory components) in soils and aquifers (Presser and Ohlendorf, 1987; Presser and others, 1990; Presser, 1994a; Presser and Piper, 1998). A summary of selenium concentration and load data, which provide the basis of this conceptual model of selenium sources, transport, and mobility, also is given in figure A6.

The San Joaquin Valley has a net negative annual water budget (evaporation exceeds precipitation). Prior to development of a water management system, a permanent shallow groundwater table only occurred in groundwater discharge zones near the valley 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.

Estimates of geologic and hydrologic reservoirs of selenium within the alluvial fans and in the valley provide perspective on the amount of selenium potentially available for discharge through a drainage conveyance. Such estimates are necessary to understand the minimum bounds on how much selenium would be discharged over the course of time, should an out-of-valley conveyance system be built. Relating the size of selenium reservoirs to an estimate of the time necessary to discharge accumulated selenium in a drainage conveyance also provides planning context.

Prediction of Long-Term Selenium Reservoirs

Data collected from the Panoche Creek alluvial fan area allows preliminary calculations of the reservoir of selenium

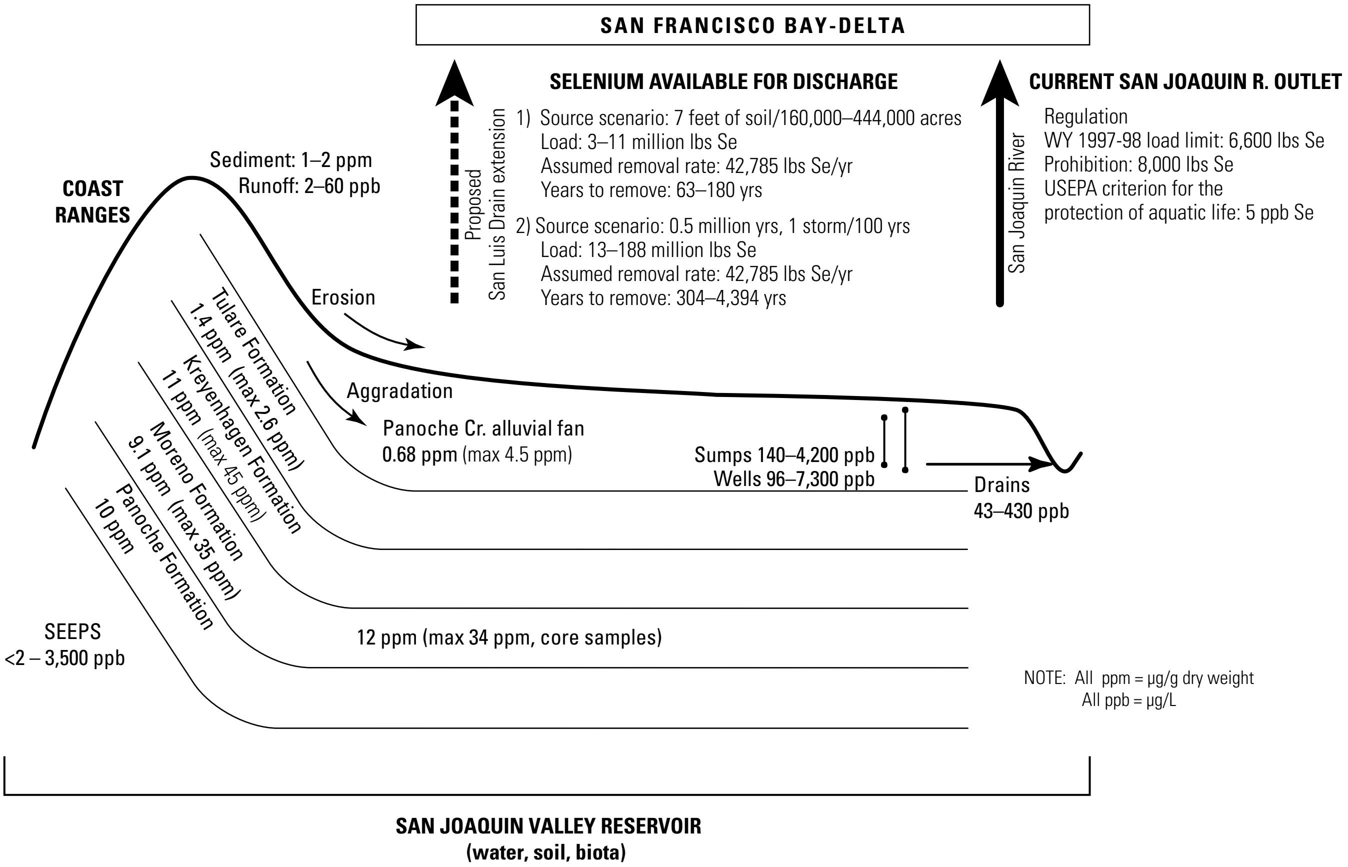


Figure A6. Schematic diagram of selenium sources of the Coast Ranges and the accumulated reservoir of selenium within the western San Joaquin Valley.

Table A2. Predicted selenium reservoir in the San Joaquin Valley based on alluvial fill (an average soil selenium concentration applied to different affected acreages, soil densities, and soil depths).

[Selenium concentration in soil is dry weight. Applied problem acreage is from Drainage Program (1990s); applied alluvial farm acreage is from Bull (1964). For assumed removal rate, see main text table 5 or generalization of 42,704 lbs selenium per year based on 314,000 acre-ft of drainage at a selenium concentration of 50 µg/L. A kesterson (kst) is 17,400 lbs selenium (see previous discussion and Presser and Piper, 1998).]

Applied acreage (acres)	Depth (meters)[a]	Density (g/cm^3)[a]	Soil[b] (µg/g selenium)	Reservoir (million lbs selenium)	ksts	Assumed removal rate (million lbs selenium/year)	Years of loading to Bay/Delta
Problem acreage scenario[c]							
444,000	2 (6.6 ft)	2.0	0.68	10.8	621	0.043	252
444,000	2	1.46	0.68	7.7	442	0.043	180
444,000	15 (50 ft)	1.46	0.68	59	3,391	0.043	1,379
444,000	91 (300 ft)	1.46	0.68	356	20,460	0.043	8,321
Panoche Creek alluvial fan acreage scenario[a]							
160,000	2	1.46	0.68	2.7	155	0.043	63
160,000	15	1.46	0.68	20.3	11,667	0.043	474
160,000	91	1.46	0.68	123	7,069	0.043	2,875

[a] Bull, (1964).

[b] Tidball and others, (1986 and 1989).

[c] Drainage Program, (1990a).

within the alluvial fans of the San Joaquin Valley; that is, the selenium potentially available for discharge through a drainage conveyance over the long-term. Two methodologies are presented here for estimating selenium reservoirs and consequently determining the time necessary to discharge the accumulated selenium from the alluvial fans of the valley. The methodologies are based on:

- concentrations of selenium in soils of the western San Joaquin Valley and estimates of either Panoche Creek alluvial fan area acreage or *problem acreage*, but neglecting the amount of selenium in groundwater reservoirs; or
- suspended and dissolved selenium loads brought down in runoff from the Coast Ranges in the Panoche Creek alluvial fan area.

Methodology Based on Alluvial Fill—Soils Scenario

General surveys of selenium concentrations in soils across the western United States show an average of 0.34 µg/g (all soil concentrations are in dry weight), although sampling was limited (Shacklette and Boerngen, 1984). The average is 0.26 µg/g across the conterminous United States. Surveys of selenium concentrations in soils of the western San Joaquin Valley were conducted in 1982 and 1985 (Tidball and others, 1986; 1989). The interfan area below Monocline Ridge and between Panoche Creek in the north and Cantua Creek in the south showed the highest selenium concentrations (maximum ungridded value 4.5 µg/g). The geometric mean for the Panoche Creek alluvial fan was 0.68 µg/g selenium (721 sites, 1.6 kilometer interval, 66 to 72 inch depth). Tidball and others (1986, 1989) also found a geometric mean of 0.14 µg/g for the San Joaquin Valley western slope (297 sites, 10 kilometer intervals, 0 to 12 inch depth).

An average soil concentration of 0.68 µg/g selenium was employed here along with several estimates of affected acreage, soil densities, and soil depths to estimate the amount of selenium in the soil reservoir of the Panoche Creek alluvial fan area (table A2). Predicted selenium deposition under the various modeled conditions range from 2.7 to 356 million lbs selenium. If a removal rate of 42,785 lbs per year is hypothesized (see main text and later discussion, appendix B), it would take 63 to 8,321 years to discharge the calculated soil reservoir of selenium (table A2) (fig. A6). This estimate does not factor in loading that would occur over the course of that time due to further weathering and runoff from the Coast Ranges, nor the amount of selenium in groundwater reservoirs

Methodology Based on Panoche Creek Runoff—Runoff Scenario

Runoff was transported in WY 1995 in the existing section of the San Luis Drain when extreme flooding in the Coast Ranges caused the drain to be used as a runoff collector system. A selenium load estimated at 1,750 lbs was eventually discharged via the drain to the San Joaquin River (Central

Valley Board, 1996a,b; Presser and Piper, 1998). This amount represents 22 percent of the annual 8000-pound selenium prohibition for discharge to the San Joaquin River enacted by the State in 1996. The runoff load for the one major storm of WY 1997 was estimated at 137 lbs selenium based on monitoring downstream channels (USBR and others, 1998 and ongoing; appendix B, table B8). This amount represents 1.9 percent of the annual load discharged to the San Joaquin River in WY 1997. In 1998, 487 lbs selenium was estimated transported by Coast Ranges runoff, representing 5 percent of the total load discharged though the Grassland Bypass Channel Project (USBR and others, 1998 and ongoing). These latter data represent approximations of anecdotal events and should only be used to assess an order-of-magnitude for runoff loads during a series of short duration storms (total precipitation of 0.6 inches) in WY 1997. Comparison then can be made to the amount discharged in an extremely wet year in WY 1995 (total precipitation greater than 11.5 inches).

No complete sets of data (flow, selenium concentration in water and sediment, and amounts of sediment) are available for Panoche Creek alluvial fan area, the area of greatest selenium source influx, prior to 1997. Reconnaissance in 1987 to 1988 (Presser and others, 1990) showed dissolved selenium concentrations of 44 to 57 µg/L in runoff samples. Suspended sediment selenium concentrations were relatively low (1.2 to 2.9 µg/g selenium), but the volume of sediment relatively high (10 percent or 91,500 mg/L).

The rate of sediment and selenium source influx has been under study at Panoche Creek since September 1997 (U.S. Geological Survey, 1999; Kratzer and others, 2003). A recently installed gaging station provided flow data and hydrographs for WY 1998 storms. Storms of WY 1998 were the result of an *El Niño* year of precipitation and therefore represent an extremely wet year (see below, occurrence interval of large magnitude storms). Sediment and water samples were taken during flood events to determine dissolved, total, and suspended selenium loads (U.S. Geological Survey, 1999; Kratzer and others, 2003). Flow data are integrated here with these selenium concentration data to calculate dissolved and total selenium loads, with suspended selenium loads calculated by difference (table A3). The calculated selenium load was 5,995 lbs selenium for runoff discharged from Panoche Creek during two storms (table A3). Estimation here of two intervening storms showed a total of 2,050 lbs. The total is 8,045 lbs for runoff loads of selenium for WY 1998, with 16 percent of the load as the dissolved fraction and 84 percent as

Table A3. Selenium loads generated in upper Panoche Creek watershed during storms of WY 1998 and in lower Grassland area watershed during WY 1997.

[Storm runoff for WY 1998 was measured at Panoche Creek at highway I-5 by USGS; sampling during these storms was on a limited basis because of the large magnitude of some events (USGS, 1999; Kratzer and others, 2003). The integrated area under the hydrograph for WY 1998 is used here with total and dissolved selenium concentration data to calculate selenium load; suspended load is calculated by difference. Upper watershed loads measured for WY 1998 may represent maximum infrequent loading through Panoche Creek, rather that being representative of annual historic loading (see text for detailed discussion). The selenium loads for WY 1998 form the basis for predicting the magnitude of geologic and hydrologic selenium reservoirs in the western San Joaquin Valley (see Table A4, one large magnitude storm per 10, 50 or 100 years). Loads for WY 1997, given for comparison, were measured as amount discharged as overflow to a wetland slough in the Grassland subarea (USBR and others, 1998 and ongoing).]

Storm dates	Duration (hours)	Initial flow (ft^3/s)	Maximum flow (ft^3/s)	Ending flow (ft^3/s)	Dissolved selenium (lbs)	Suspended selenium (lbs)	Total selenium(lbs)
WY 1998							
February 3–4	34.8	310	8,000	750	640	3,850	4,490
February 6–7	28.0	1,800	2,800	200	179	699	878
February 8 (approximated)	–	–	6,500[a]	–	50	–	1,800
February 19–20 (approximated)	–	–	1,600[a]	–	30	–	250
February 21–22	28.5	2	1,400	220	76	236	312
February 23–24	21.8	510	2,100	180	67	248	315
SUBTOTAL (measured storms)	–	–	–	–	962 (16%)	5,033 (84%)	5,995
TOTAL (all storms)	–	–	–	–	–	–	8,045
WY 1997							
January and February, 1997[b]	–	–	–	–	–	–	137
TOTAL WY 1997	–	–	–	–	–	–	137

[a] Flow is approximated from gage height measurements, making load values generated from these flows also approximate; selenium concentrations are assigned for these two storms.

[b] See table B9.

Table A4. Selenium concentrations in suspended sediment (silt and clay fraction; sand fraction) associated with storms of February, 1998.

[Selenium analysis by hydride generation, with a detection limit of 0.1 µg/g. Storms are those illustrated in table A3 for February 3–4 and 6–7, 1998. Time is expressed as military time.]

Date and time		Suspended sediment selenium (µg/g dry weight) Silt and clay fraction (<0.062 mm)	Sand fraction (< 2 mm)
2/3/98	3:00	1.2	–
2/3/98	7:00	1.5	0.9
2/3/98	10:30	1.4	0.9
2/3/98	12:00	1.4	1.1
2/3/98	14:00	1.5	1.0
2/3/98	16:00	1.4	0.8
2/3/98	19:00	1.3	0.6
2/4/98	0:00	1.2	0.8
2/4/98	7:00	1.1	0.8
2/6/98	11:40	1.5	0.8
2/6/98	12:40	1.5	1.0
2/6/98	13:40	1.3	1.1
2/6/98	15:30	1.4	1.0
2/6/98	18:30	1.4	0.9
2/6/98	22:30	1.4	0.8
2/7/98	3:30	1.4	1.0
2/7/98	9:30	1.4	0.8

the suspended fraction. Although the concentration of selenium in suspended sediment is relatively low (0.6 to 1.5 µg/g dry weight) (table A4), the large volume of material leads to a high load in the particulate material as compared to the dissolved load (also see Presser and others, 1990). Calculations cannot be made at this time to estimate the load of selenium discharged from the watershed to receiving waters to compare to input loads because of the lack of adequate downstream monitoring stations (Presser and Piper, 1998). So influx and efflux cannot be directly compared. However, 8,045 lbs per year source selenium influx measured in the extremely wet year of 1998 is comparable to the State limitation on discharge from the San Joaquin Valley through the San Joaquin River, that is, an efflux of 8,000 lbs per year (Central Valley Board, 1996c). In general though, under average rainfall amounts, the annual load from these natural sources is calculated to be a small percentage of the selenium load potentially discharged from the San Joaquin Valley (USBR and others, 1998 and ongoing). Only when source loads from the Coast Ranges are considered in sum (see discussion below) or during a year in which a large magnitude storm occurs, are the influx amounts significant compared to efflux amounts currently regulated.

Selenium discharge data for Panoche Creek for WY 1998 were extrapolated here to give estimates of the amount of selenium deposition that has occurred over a time period of either 0.5 million years or 1.1 million years to give a range of accumulation. Deposition over these two time periods was calculated for a) one large magnitude storm in 10 years; b) one large magnitude storm in 50 years; or c) one large magnitude storm in 100 years. Table A5 shows amounts of total, dissolved, and suspended selenium deposited under those conditions. The range of dissolved selenium deposition over 0.5 million years is 13 to 86 million lbs selenium; and over the course of 1.1 million years, 28 to 188 million lbs selenium. The range of suspended selenium deposition over the course of 0.5 million years is 67 to 449 million lbs selenium; and over the course of 1.1 million years, 147 to 989 million lbs selenium. The range of total selenium deposition over the course of 0.5 million years is 80 to 535 million lbs; and over the course of 1.1 million years, 175 to 1,177 million lbs selenium. If the selenium removal rate is hypothesized as 42,785 lbs per year (0.043 million lbs per year) (see later discussion, appendix B), then it would take 1,870 to 27,510 years to discharge this reservoir of selenium in the Panoche Creek alluvial fan based on total selenium deposition from runoff (table A5) (fig. A6). Ranges based on dissolved selenium deposition from runoff are 304 to 4,394 years; and based on suspended selenium deposition from runoff are 1,566 to 23,116 years. These estimates do not factor in the loading that would occur over the course of that time due to further weathering and runoff from the Coast Ranges. The estimate does attempt to include selenium in the groundwater reservoir.

Characteristics and Timing of Selenium Source Water Release as Drainage

Mobility of Selenium: Source Flow, Concentration, and Load

The behavior and speciation of selenium, and hence its solubility and mobility, are determined by a combination of processes including inorganic (for example, weathering of the Coast Ranges) and organic (for example, oxidation by bacteria) reactions. Oxidative reactions are partly responsible for selenium mobility from source geologic formations of the Coast Ranges and the adjacent derived alluvial fans of the San Joaquin Valley (Presser and others, 1990; Gilliom and others, 1989; Presser, 1994b) (fig. A7). Selenium is oxidized to selenate, a form readily soluble in water. Selenate is mobile in aqueous systems as a function of oxygen flux or availability of oxygen and/or water in weathered rocks and soils. As oxygen saturation is reached, the rate of reaction may approach a constant value and selenium remains in its highest oxidation state (+6, $SeO_4^{=}$) (fig. A7). Source agricultural drainage waters are selenate-dominated, a fact of major significance in deter-

Table A5. Predicted selenium reservoir in the San Joaquin Valley based on Panoche Creek storm runoff (deposition and recharge) (see Table 3A for data used for extrapolation).

[For assumed removal rate, see main text table 5 or generalization of 42,704 lbs per year selenium based on 314,000 acre-ft of drainage at a selenium concentration of 50 µg/L. A kesterson (kst) is 17,400 lbs selenium (see previous discussion)]

Runoff scenario (deposition and recharge)	Total selenium [dissolved plus suspended] (million lbs)	Dissolved selenium [assumed as 16% of total] (million lbs)	Suspended selenium [assumed as 84% of total] (million lbs)	ksts (range)	Assumed removal rate (million lbs selenium/year)	Years of loading to Bay-Delta [range based on total selenium]	Minimum years of loading to Bay-Delta [based on dissolved selenium]
0.5 million years 1 large magnitude storm year/10 years	345–535	55–86	290–449	3,161–30,747	0.043	8,064–12,504	1,285
0.5 million years 1 large magnitude storm year/50 years	140–387	22–62	118–325	1,264–22,241	0.043	3,272–9,045	514
0.5 million years 1 large magnitude storm year/100 years	80–188	13–30	67–158	747–10,804	0.043	1,870–4,394	304
1.1 million years 1 large magnitude storm year/10 years	759–1,177	121–188	638–989	6,954–67,644	0.043	17,740–27,510	2,828
1.1 million years 1 large magnitude storm year/50 years	240–499	38–80	201–420	2,184–28,678	0.043	5,609–11,663	888
1.1 million years 1 large magnitude storm year/100 years	175–415	28–66	147–348	1,609–23,850	0.043	4,090–9,700	654

mining the mobility of selenium in surface-water and groundwater systems and, hence, the extent and impact of selenium in drainage water discharges (such as subsurface drainage) from those systems.

The effect of a large reservoir of selenium on recent subsurface drainage flow (potentially discharged source waters) is illustrated in figure A8. Figure A8 is generalized from data collected (USBR and others, 1998 and ongoing) during frequent sampling of drainage source water (current agricultural discharges to the San Joaquin River in WYs 1997 and 1998 from the Grassland subarea) (appendix D, figs. D15 and D16). Flow or discharge increases with increased water flux (applied irrigation or precipitation). The concentration of selenium in the discharged source agricultural wastewater increases as water flux increases. Only at elevated water fluxes seen during extremely wet years (the maximum rainfall occurring in a February over a 50-year record) does a dilution effect occur, lowering the concentration. The higher concentrations of selenium discharged under high flow conditions are

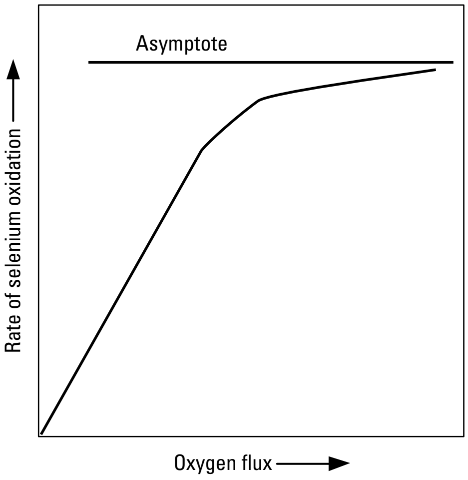


Figure A7. Generalized selenium oxidation rate as a function of oxygen flux.

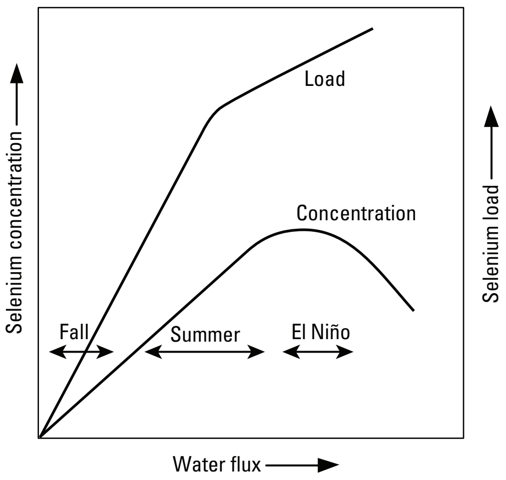


Figure A8. Generalized selenium load and selenium concentration as a function of water flux.

an indication of the magnitude of the selenium reservoir and the conditions under which displacement of variable-quality shallow ground water may occur. Selenium load in source water also increases as a result of increased water flux (fig. A8). The combined effect of increasing concentration and increasing flow as water flux increases assures an increase in selenium load discharged as more irrigation water is applied or more precipitation falls.

Control and Timing

During 1986 to 1998, the highest annual loads from agricultural drainage in the San Joaquin Valley (fig. A9) were discharged in years of normal or above average precipitation (Central Valley Board, 1996b, c; 1998d, e, f, g, h; 2000b, c; Department of Water Resources, 1986 to 1998) (fig. A10) (also see later discussion). Regulatory load targets also are highest during February, March, April, and May, reflecting agricultural practices (fig. A11) (USBR, 1995; Central Valley Board, 1996c, 1998a). It is possible that dilution afforded during wetter years by the increased volume of water in rivers could decrease salt and selenium concentrations at compliance points in the San Joaquin River or in the Bay-Delta, especially seaward from the inflows of the Sacramento River. The extent of dilution depends upon uncontaminated water inputs relative to San Joaquin River loads. However, selenium and salt concentrations do not necessarily decrease in wet years in agricultural drainage water itself, or in agricultural drainage canals where discharge is predominantly selenium-laden water (fig. A7). An out-of-valley agricultural drainage discharge to the Bay-Delta also may be subjected to these natural or seasonal effects (see later discussions on modeled discharge to the San Joaquin River). The effect could be larger loads discharged to receiving waters during wet seasons than might otherwise be expected through management.

Control of release of agricultural discharge to take advantage of the high-volume river flows was suggested in 1955, when the San Luis Drain was planned, and throughout many of the later planning reports (such as Interagency Drainage Program, 1979a, b). In 1997, the State Board Draft Environmental Impact Report (DEIR) for Implementation of the 1995 Bay-Delta Water Quality Control Plan concluded that scheduling the release of subsurface agricultural drainage from the western San Joaquin Valley is crucial to meeting the Bay-Delta water-quality standards, including salinity (State Board, 1997). Further documentation in the DEIR of future drainage systems conceptualized the temporary control of potential drainage discharges stored in the soil profile using a system of valves, weirs, and sumps. A similar management technique using *DO-SIR* valves is in practice in the Grassland subarea to enable storage of subsurface drainage [Grassland Area Farmers, 1997; USBR and others, 1998 and ongoing]. Grassland area farmers in discussions with regulators have pointed out the effect of this type of storage technique by calculating the amount of

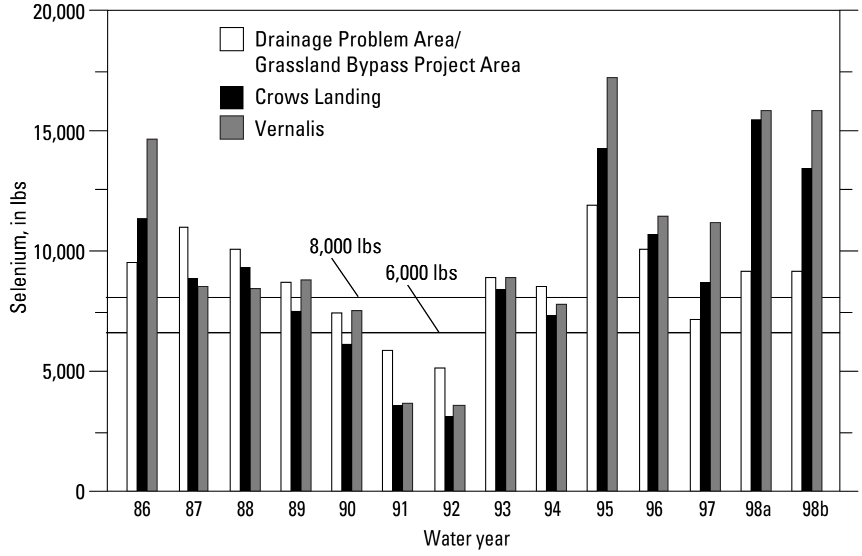


Figure A9. Selenium load for Drainage Problem Area/Grassland Bypass Project Area, San Joaquin River at Crows Landing, and Vernalis for WYs 1986–1998.

selenium they *have not discharged* to the San Joaquin River on an annual basis (for example, WY 1997, 3,680 lbs selenium *not discharged or stored* compared to 7,097 lbs selenium discharged) (USBR and others, 1999). These types of drainage management activities emphasize the importance of considering changes in selenium reservoirs (storage) and of documenting a selenium inventory or mass balance, as opposed to focusing on short-term averages of discharges that represent annual leaching to sustain a year-to-year farming effort.

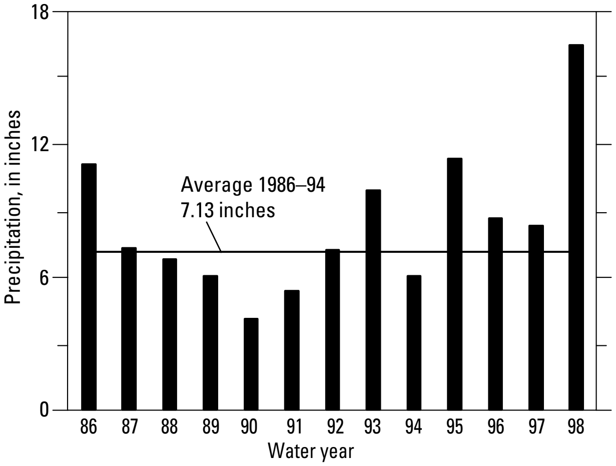


Figure A10. CIMIS (California Irrigation Management Information System) station #124 precipitation for WYs 1986–1998.

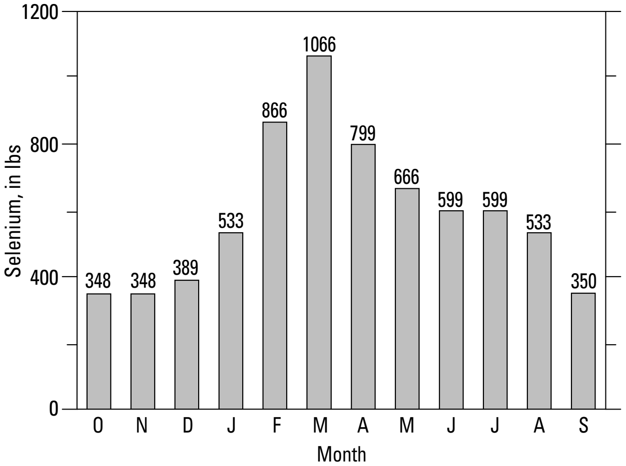


Figure A11. Monthly selenium load targets for San Luis Drain discharge to Mud Slough for WYs 1997 and 1998.

Appendix B. San Joaquin Valley Agricultural Drainage Projections

Contents

Figures

Tables

Projected Selenium Loads from Historic Data and Evidentiary Testimony

Envisioned drainage volumes were presented in earlier discussions concerning water quality conditions in groundwater aquifers and sustainability of discharge from the San Joaquin Valley (appendix A). Presented here are selenium load projections for the Westlands, Grassland, Tulare, Kern, and Northern subareas based on documentation for planning and available measurements of drainage discharge.

Westlands Water District and Subarea

Projections from Historic Data

Westlands subarea projections of selenium loads are based on 1) historic measurements of drainage discharged from Westlands Water District into the San Luis Drain from 1981 until its closure in 1986; and 2) design estimates used in testimony by Westlands Water District. Using a historical range of 330 to 430 µg/L selenium for the initial hook-up of subsurface drains to the San Luis Drain, the projected load is 6,283 to 8,187 lbs selenium per year (table B1). These amounts are higher than those estimated by the USBR as having occurred over the 57-month period of San Luis Drain operation (January 1981-September 1985, average of 4,776 lbs per year) (USBR, 1986).

A recent compilation from Westlands Water District indicated a discharge of 38,450 acre-ft from January 1981 through May 1986 (Westlands Water District, 1998). An estimated 22,660 lbs of selenium was discharged to Kesterson Reservoir during this time (USBR, 1986). This estimated input of selenium includes 17,400 lbs that were distributed in the water, biota, and sediment of Kesterson Reservoir and 5,280 lbs of selenium contained in 95,271 cubic yards of bed sediment still residing in the San Luis Drain. The cumulative 17,400-lb amount is hereafter referred to as one kesterson (kst). The kst unit represents a measure of potential cumulative hazard to wildlife based on mass loading directly released into an ecosystem (Presser and Piper, 1998). This unit will be used later to provide historical and quantitative perspectives.

Projections from Evidentiary Testimony

Evidence presented in 1996 referred to estimates prepared in 1965 for planned discharges from Westlands Water District. These estimates preceded use of management practices that place an emphasis on more efficient water use (Westlands Water District, 1996). Table B1 shows projected discharge to the San Luis Drain by 1980 in comparison to that estimated to actually have occurred from 1981 to 1985. The planning estimates were expressed as volumes of drainage or acreage to be drained. If a 330 to 430 µg/L selenium concentration range (see previous discussion) is used in conjunction with an estimate of 38,000 acre-ft of annual drainage, then the projected selenium load is 34,109 to 44,445 lbs per year from 76,000 acres in Westlands Water District (Westlands Water District, 1996). Using these estimates, projections of generated drainage and selenium are: 0.50 acre-ft of drainage per acre per year; 0.449 to 1.02 lbs selenium per acre per year; or 0.898 to 1.17 lbs selenium per acre-feet per year (table B1).

Data for selenium concentrations in drainage presently are not available from Westlands Water District because, since closure of the San Luis Drain in 1986, drainage is being stored in the subsurface (Jones and Stokes Associates, Inc., 1986a, b; Drainage Program, 1989, 1990a). This practice could potentially endanger the quality of San Joaquin Valley groundwater aquifers. The eventual loss of use of the ground water basin beneath the San Luis Unit has been predicted at various stages of planning processes as a justification for an out-of-valley drain. Trade-offs were to be among lands kept in production, water export from the Bay-Delta, groundwater quality, and San Joaquin River degradation (USBR, 1978). The Drainage Program (1990a) estimated the remaining life of the semi-confined aquifer beneath the Westlands subarea (576,000 acres) based on salinity (total dissolved solids) at a mean of 110 years. Minimum life remaining in some areas of the western San Joaquin Valley was as low as 25 years.

Several evidentiary proceedings concerning the disposition of drainage from Westlands Water District and the San Luis Unit have resulted in judgments and testimony concerning the quantity of drainage (table B2) (Westlands Water District, 1996). Annual drainage discharge from the San Luis Unit of the Central Valley Project was estimated as part of the Barcellos judgment (1986) to be an amount of discharge not greater than 100,000 acre-ft and not less than 60,000 acre-ft (USBR, 1992). Using assigned selenium concentration of 50, 150, 300 µg/L (see discussion in main text), selenium loads would range from 8,160 to 81,600 lbs per year (table B2).

Estimates of drainage from the Westlands Water District presented in testimony in 1996 were based on including 42,000 acres in the northeastern corner of Westlands Water District. Subsurface drains have been installed there, but are not connected to the San Luis Drain. The evidence stated that an additional 29.5 miles of the San Luis Drain would be constructed to reach this area, if drainage was to be provided for all areas of Westlands Water District needing drainage. An estimate of the volume of drainage (1,900 to 2,300 acre-ft per year) to be discharged upon initial reconnection to the San Luis Drain from Westlands Water District is not well justified, but is presented here for comparison to those estimates given by Westlands Water District in 1980 (7,000 acre-ft per year). The evidence presented showed a total problem acreage of 200,000 acres for Westlands Water District, with 60,000 acre-ft of drainage generated annually (Westlands Water District, 1996). This estimate represents a 0.3 acre-ft per acre per year rate of generation of drainage. Using assigned selenium concentrations of 50, 150, and 300 µg/L, projected selenium loads are 8,160 to 48,960 lbs per year from the Westlands Water District, with an initial hook-up contributing 258 to 1,877 lbs selenium (table B2).

Table B1. Westlands Water District historical data for acreage and selenium concentrations employed to project selenium loads.

Use of San Luis Drain by Westlands Water District to discharge selenium to Kesterson Reservoir	Westlands Water District planned drainage acreage/ total acreage (acres)	Problem acreage with on-farm drains (acres)	Problem drainage (acre-ft)	Selenium (µg/L)	Selenium load (lbs/time interval)	Factors (acre-ft/acre, lbs selenium/ acre-ft, or lbs selenium per yr)
San Luis Drain discharge (measurement average 1983-1984) (State Board, 1985; Westlands Water District, 1998)	–	–	38,450 (total discharge for 65 months; Jan. 1981 to May 1986)	330 – 430	–	–
Estimated Westlands Water District annual discharge to San Luis Drain from Jan. 1981 – Sept. 1985 (selenium concentrations from use of drain in 1983 – 1984) (State Board, 1985)	–	5,000 (42,000[a])	7,000	330 – 430	6,283 – 8,187/yr	0.17–1.4 acre-ft/acre; 0.898–1.17 lbs/acre-ft
Projected Westlands Water District discharge to San Luis Drain by 1980 (based on 1965 plans and selenium concentrations from use of drain in 1983 – 84) (Westlands Water District, 1996)	300,000/600,000 (approximately 566,500 irrigated acres)	76,000	38,000/yr	330 – 430	34,109 – 44,445/yr	0.50 acre-ft/acre; 0.898 – 1.17 lbs/acre-ft; 0.449 – 1.02 lbs/acre/yr
1986 Environmental Impact Statement (EIS) estimated San Luis Drain discharge (USBR, 1986): total (Jan. 1981 – Sept. 1985) or annual (total averaged over 57 months)	–	–	–	–	22,660 or 4,776/yr	–
1986 EIS estimated San Luis Drain selenium load to Kesterson Reservoir (1981– 85) (USBR, 1986)	–	–	–	–	17,400[b] (1 kst)	–
1986 EIS estimated San Luis Drain bed sediment accumulation (95,271 cubic yards) (USBR, 1986)	–	–	–	–	5,280	–

[a] Westlands Water District contends that the drainage from 5,000 subsurface-drained acres actually represents drainage from 42,000 acres because of upslope contributions drained to this downslope area (State Board, 1985).

[b] The 17,400-lb amount is referred to as one kesterson (kst). The use of this unit provides perspective on the quantity of selenium that was a hazard to wildlife when released directly to the wetland at Kesterson Reservoir (Presser and Piper, 1998).

Grassland Subarea (WYs 1986 – 1996)

Projections from Historic Data

Provision of a drainage outlet was initially focused on Westlands Water District, but drainage specifications actually apply to a larger area designated as the San Luis Unit of the Central Valley Project (USBR, 1992) (fig. A1). Westlands Water District within the San Luis Unit is referred to as the San Luis Service Area (irrigation service from the San Luis Canal portion of the California Aqueduct). Parts of the Grassland area within the San Luis Unit are referred to as the Delta-Mendota Service Area (irrigation service from the Delta-Mendota Canal). In general, the Grassland problem area considered here has approximately 100,000 acres in production, with 50,000 acres requiring subsurface drainage. Designated zones within the Grassland subarea are mainly based on water quality: zone A, 72,000 acres; Zone B, 14,000 acres; and Zone C, 30,000 acres (table B3) (Drainage Program, 1990a). Zone A is projected to generate drainage of poor enough quality to impair State beneficial uses for receiving waters and therefore is a focus of drainage analysis. The water and drainage districts of the Grassland subarea continue to consolidate into regional groups based on varying needs and legal ramifications, adding to already complex historical alignments (USBR, 1992; Environmental Defense Fund, 1994). The area generally generates blended subsurface drainage that is discharged out of the region through the San Joaquin River.

Discharge of selenium from the State-designated Grassland Drainage Area to the San Joaquin River has been moni-

Table B2. Projections of annual selenium loads discharged to a San Luis Drain extension using 1) evidentiary estimates and selenium concentrations of 50, 150, and 300 µg/L for Westlands Water District drainage; and 2) 62.5 µg/L applied to 30,000 to 40,000 acre-feet of drainage for Grassland Area Farmers.

[This scenario includes resumption of discharge to the San Luis Drain by Westlands Water District and continuing discharge by Grassland Area Farmers to a 28-mile portion of the San Luis Drain under the Grassland Bypass Channel Project Data sources: USBR, 1992; Westlands Water District, 1996).]

Westlands subarea or San Luis Unit	Problem drainage (acre-ft)	Factor (acre-ft/acre)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)
Barcellos Judgment	not < 60,000 not > 100,000	–	50	8,160– 13,600	150	24,480– 40,800	300	48,960– 81,600
Planning Alternatives	24,000	0.23	50	3,264	150	9,792	300	19,584
Initial hook-up of 7,600 acreage of on-farm drains	1,900– 2,300	–	50	258– 313	150	775– 938	300	1,550– 1,877
Drainage of 200,000 acres of problem acreage	60,000	0.30	50	8,160 (0.041 lbs /acre; 0.136 lbs/acre-ft)	150	24,480 (0.122 lbs/ acre; 0.408 lbs/acre-ft)	300	48,960 (0.245 lbs/ acre; 0.816 lbs/acre-ft)
Grassland Area Farmers	30,000– 40,000[a]	–	62.5[a]	5,100– 6,800	62.5[a]	5,100– 6,800	62.5[a]	5,100– 6,800
Total (Westlands and Grassland)	90,000– 100,000	–	–	13,518– 15,273	–	30,355– 32,218	–	55,610– 57,637

[a] Measured in WY 1997 (see appendix B, table B8).

Table B3. Grassland subarea loads to the San Joaquin River for years 2000 and 2040 using Drainage Program drainage volumes and selenium concentrations for Zones A, B, and C (Drainage Program, 1989; 1990a).

	Drainage Program 2000						Drainage Program 2040			
Grassland subarea	Projection (drained acres)[a]	Projection (acre-ft of problem water)[b]	Projection (acre-ft discharged to San Joaquin River)[b]	Projected selenium (µg/L)[b]	Projected selenium load (lbs/ year)	Factor (lbs/ acre-ft)	Projection (acre-ft discharged to San Joaquin River)[b]	Projected Selenium (µg/L)[b]	Projected selenium load (lbs/ year)	Factor (lbs/ acre-ft)
Zone A	72,000	54,000	10,700	150	4,366	0.408	21,000	75	4,284	0.204
Zone B	14,000	10,600	7,000	2	38	0.0054	17,600	2	96	0.0054
Zone C	30,000	22,000	22,000	2	120	0.0054	63,500	2	345	0.0054
Total	116,000	86,600	39,700	–	4,524	–	102,100	–	4,725	–

[a] Drainage Program (1989), page 4-23 (assumption, drained acres will more than double by year 2000).

[b] Drainage Program (1990a) table 29 and page 139.

tored since 1986 (Central Valley Board, 1996b, c, 1998 d, e, f, g; h; 2000b, c; Henderson and others, 1995; USBR and others, 1998 and ongoing). Drainage discharge was through Grassland area wetland channels to San Joaquin River during this period, with the drainage configuration changing in 1997 (see discussion below, discharge through the San Luis Drain and Mud Slough to the San Joaquin River). Selenium load summaries at four monitoring sites from WY 1986 to 1998 in this area are given in tables B4 through B7.

Selenium is persistently discharged from the Grassland area to the San Joaquin River, but selenium loads depend on monitoring-site location within the Grassland area because of uptake and release of selenium throughout the watershed (tables B4–B7). The upstream drainage source discharge represents managed components of flow and load. However, annual data are not available from individual farm-field sumps to help qualify source-area shallow groundwater conditions and determine long-term variability in selenium concentrations. Affected downstream sites reported here are the San Joaquin River at Crows Landing/Patterson (CL/PATT, about 50 miles downstream from the farm agricultural discharge sumps), and the San Joaquin River at Vernalis (VERN, about

130 miles downstream from the agricultural discharge). Data for WY 1986 to 1998 generally can be related to physical variables that affect drainage conditions (see, for example, appendix A, fig. A10, annual rainfall measured at station #124, Department of Water Resources database http://www.ceresgroup.com/col/weather/cimis). Noted climatic changes during this time period are: drought from 1987 through 1992; flooding in the Coast Ranges in 1995; and flooding in the Sierra Nevada and San Joaquin Valley in the winter of 1997–98 as a consequence of El Niño conditions. Specific variables affecting selenium load are discussed in appendix D.

For management purposes, analysis of loads for WYs 1986 to 1988 showed an annual average of 10,850 lbs selenium per year (Environmental Defense Fund, 1994). For WYs 1986 to 1998, the range of managed source selenium loads is from 5,083 to 11,875 lbs per year (table B4). For the same time period, the range of annual loads for the State compliance point for the San Joaquin River at Crows Landing is 3,064 to 15,884 lbs per year (table B6). The range of loads for the San Joaquin River at Vernalis, considered the entrance to the Bay-Delta, is 3,558 to 17,238 lbs per year (table B7). Higher loads in recent years (San Joaquin River at Crows Landing, 8,667 lbs in WY 1997; and 15,501 lbs in WY 1998) are noteworthy because they occur after issuance of (1) State agricultural drainage control plans issued in 1985; (2) joint Federal-State agricultural drainage management plans issued in 1990; (3) a State limitation for annual drainage to the San Joaquin River of 8,000 lbs selenium adopted in 1996 (Central Valley Board, 1996c and 1998a, h; USBR and others, 1998 and ongoing; and see also appendix A, fig. A9).

For WYs 1986 through 1998, the cumulative selenium load discharged to the San Joaquin River at Crows Landing/Patterson was 114,879 lbs selenium (table B6). This equates to 6.6 kestersons (ksts) as a measure of potential cumulative hazard based on load (see later discussion) (Presser and Piper, 1998). However, these data compilations may not represent all sources, reservoirs, and discharges of selenium for the San Joaquin River system. For example, unregulated sumps discharge agricultural drainage into the Delta-Mendota Canal and other potential sources of selenium are outside of regulated areas (Central Valley Board, 2000d and 2002; USBR, 2002b).

As described earlier as context for future discharges, regulatory enactments of Daily or Total Maximum Monthly Load models call for discharges of 1,001 to 3,088 lbs selenium per year from the Grassland subarea by the year 2010 (also see appendix C).

Grassland Bypass Channel Project (Reuse of the San Luis Drain, WY 1997 to present)

In 1990, the Drainage Program considered re-routing drainage from the Grassland subarea through reuse of a portion of the San Luis Drain to avoid wetland contamination (drainage through the San Luis Drain and Mud Slough to San Joaquin River). Table B3 shows estimates by the Drainage Program of potential drainage from the zones of the Grassland subarea. A selenium concentration of 2 µg/L was assumed in both drainage from wetlands (Zone B) and in discharges from drained areas (Zone C). The discharge from the 72,000-acre Zone A was estimated at either 10,700 acre-ft containing a selenium concentration of 150 µg/L; or 21,000 acre-ft containing a selenium concentration of 75 µg/L. The projected selenium load from the entire Grassland subarea is 4,524 lbs and 4,725 lbs for year 2000 and 2040, respectively. These planning values are less than the loads measured historically (tables B4 to B7) and those more recently through the Grassland Bypass Channel Project (see below and table B8).

Consideration of a project to re-open part of the San Luis Drain for use by the Grassland subarea was of enough concern to elicit a U.S. Congressional hearing in 1993 (U.S. House of Representatives, 1993). Although, environmental concerns were voiced, the interim-use project was seen as a way to relieve the pressure of the long-standing agricultural drainage problem in the San Joaquin Valley. In September 1996, the USBR initiated the Grassland Bypass Channel Project to reopen a 28-mile portion of the San Luis Drain on an interim five-year basis (USBR, 1995). Cooperative support for the project among agriculture, environmental groups,

Table B4. Annual acre-feet, selenium concentrations, and selenium loads from the Grassland Area Farmers Drainage Problem Area.

[Data sources: Central Valley Board, 1996b, c; 1998d, e, f, g, h; 2000b, c; USBR and others, 1998 and ongoing.]

Water-year	Drainage (acre-ft/year)	Selenium (µg/L)	Selenium load (lbs/year)	Factor (lbs selenium/acre-ft)
1986	67,006	52.3	9,524	0.142
1987	74,902	53.8	10,959	0.146
1988	65,327	56.8	10,097	0.154
1989	54,186	59.2	8,718	0.161
1990	41,662	65.2	7,393	0.177
1991	29,290	73.5	5,858	0.200
1992	24,533	76.2	5,083	0.207
1993	41,197	79.0	8,856	0.215
1994	38,670	80.5	8,468	0.219
1995	57,574	75.8	11,875	0.206
1996	52,978	70.0	10,034	0.189
1997[a]	37,483	62.5	7,097	0.186
1998[a]	45,858	66.9	9,118	0.199
TOTAL	–	–	113,080 (average 8,698)	–

[a] Measured at San Luis Drain discharge to Mud Slough (site B) after initiation of Grassland Bypass Channel Project.

Table B5. Annual flow, selenium concentrations, and selenium loads from Mud and Salt Sloughs.

[Central Valley Board, 1996b, c; 1998d, e, f, g, h; 2000b, c; USBR and others, 1998 and ongoing.]

Water-year	Flow (combined Mud and Salt Sloughs) (acre-ft/year average)	Selenium (combined Mud and Salt Sloughs) (µg/L average)	Selenium load (combined Mud and Salt Sloughs) (lbs/year)	Mud Slough (µg/L monthly average range)	Salt Slough (µg/L monthly average range)
1986	284,316	8.6	6,643	2.3–22	1.4–22
1987	233,843	12.0	7,641	1.7–26	5.2–26
1988	230,454	13.0	8,132	1.4–18	1.6–27
1989	211,393	14.1	8,099	0.7–5.0	2.7–33
1990	194,656	14.6	7,719	0.6–8.1	4.2–36
1991	102,162	14.0	3,899	0.7–38	0.9–30
1992	85,428	12.6	2,919	0.8–48	0.6–27
1993	167,955	15.0	6,871	1.0–5.0	0.5–42
1994	183,546	16.0	7,980	0.5–22	1.2–44
1995	263,769	14.9	10,694	0.7–4.2	0.8–38
1996	267,344	13.0	9,697	–	–
1997	288,253	10.0	7,722	5.0–80	0.5–3.4
1998	378,506	14.0	10,446	6.9–67.3	0.6–4.0
TOTAL	–	–	98,462 (8,890 average)	–	–

Table B6. Annual flow, selenium concentrations, and selenium loads measured at the San Joaquin River near Crows Landing/Patterson.

[Data sources: Central Valley Board 1996b, c; 1998d, e, f, g, h; 2000b, c; USBR and others, 1998 and ongoing.]

Water-year	Flow (average million acre-ft/year)	Selenium (average µg/L)	Selenium load (lbs/year)	Selenium (monthly average µg/L range)
1986	2.67	1.6	11,305	<1–4
1987	0.66	4.9	8,857	3.6–12
1988	0.55	6.2	9,330	0.8–12
1989	0.44	6.3	7,473	3.4–17
1990	0.40	5.6	6,125	1.6–13
1991	0.29	4.5	3,548	0.9–11
1992	0.30	3.7	3,064	0.7–11
1993	0.89	3.5	8,379	0.4–8.0
1994	0.56	4.8	7,270	<0.4–13
1995	3.50	1.6	14,291	0.6–12
1996	1.44	3.0	10,686	–
1997	4.18[a]	1.0	8,667[a]	0.1–10
1998	5.13	–	15,501	0.4–4.1
TOTAL	–	–	114,496 (8,807 average/yr)	–

[a] Data from the Grassland Bypass Channel Project shows 3.713million acre-ft and 9,054 lbs for WY 1997.

Table B7. Annual flow, selenium concentrations, and selenium loads measured at the San Joaquin River near Vernalis.

[Data sources: Central Valley Board 1996b, c; 1998d, e, f, g, h; 2000b, c; USBR and others,1998 and ongoing.]

Water-year	Flow (average million acre-ft/year)	Selenium (average µg/L)	Selenium load (lbs/year)	Selenium (monthly average µg/L range)
1986	5.22	1.0	14,601	<0.1-1.4
1987	1.81	1.8	8,502	0.6-3.2
1988	1.17	2.7	8,427	0.8-4.0
1989	1.06	3.0	8,741	1.7-6.8
1990	0.92	3.0	7,472	0.8-9.6
1991	0.66	2.0	3,611	0.5-4.8
1992	0.70	1.9	3,558	0.4-4.4
1993	1.70	1.9	8,905	<0.4-6.1
1994	1.22	2.3	7,760	0.4-6.3
1995	6.30	1.0	17,238	0.5-3.5
1996	3.95	1.1	11,431	–
1997	6.77	0.6	11,190	–
1998	8.50	–	15,810	–
TOTAL	–	–	127,246 (9,788 average/yr)	–

and government included a regional drainage analysis and an approach to controlling non-point source pollution that integrated tradable permits and incentives (Environmental Defense Fund, 1994). The collector drain now transports drainage more directly to the San Joaquin River, thereby removing it from wetland channels. The goals include (1) measuring and eventually reducing drainage loads through a regional program; (2) protecting riparian wildlife habitat by assuring wetlands of an adequate clean-water supply; and (3) monitoring the effects that result from re-routing of drainage. A regional drainage agency that includes local water and drainage districts is assigned responsibility for pollution. A Federal/State interagency committee monitors flow, water quality, sediment quality, biota, and toxicity in the San Luis Drain, Mud Slough, Salt Slough, and the San Joaquin River (USBR and others, 1996). Monetary penalties for exceedance of loads have been agreed upon and a long-term management strategy to achieve water-quality objectives is being developed (Grassland Area Farmers and San Luis Delta-Mendota Water Authority, 1998).

Selenium load targets for the reuse of the San Luis Drain are defined by the commitment that the input loads to the San Joaquin River *will not worsen* over historical loads (USBR, 1995). Appendix A (fig. A11) shows the monthly load targets adopted for the first two years of the Grassland Bypass Channel Project. Compliance loads are measured at the discharge of the San Luis Drain into Mud Slough rather than at the San Joaquin River at Crows Landing, as previously regulated by the State (Central Valley Board, 1996c). In September 1998, a State waste discharge permit was issued for the Grassland Bypass Channel Project which contained negotiated load targets (Central Valley Board, 1998a). Tables B8 to B10 show annual and monthly load targets for 1997 through 2001. The target is 6,660 lbs for each of the first two years of the project with a 5 percent reduction each year for the next three years. If the annual target amount is exceeded by 20 percent, consideration would be given to shutting down the San Luis Drain and terminating the Grassland Bypass Channel Project (USBR, 1995). During the first two years of the project, loads were above load targets. It is also notable that drain water discharged to the San Joaquin River through the San Luis Drain is more consistently concentrated than were historic discharges to the wetlands channels system. Wastewater in the San Luis Drain is not diluted by wetlands flows and loss of selenium to sediment and biota, as occurred during transit through wetland channels (*in-transit loss*), may be reduced (USBR, 1995; Presser and Piper, 1998). Adoption by the State of a water-quality objective of less than 2 µg/L selenium for the Grassland wetland channels as promulgated by USEPA (USEPA, 1992; Central Valley Board, 1996c,

Table B8. Acreage, annual discharge, selenium concentrations, and selenium loads for the Grassland Bypass Channel Project (reuse of a 28-mile portion of the San Luis Drain) for WYs 1997 and 1998 and selenium load target for regulatory purposes.

Use of San Luis Drain by Grassland Area Farmers (Grassland subarea Zone A) for discharge of selenium to the San Joaquin River	Problem acreage (acres)	Problem water or drainage (acre-ft)	Selenium (µg/L)	Selenium load (lbs/year)	Factor (lbs selenium/ acre or acre-ft)	Factor (acre-ft/ acre)
Central Valley Board limitation of selenium discharge to the San Joaquin River or tributaries from tile or open drainage systems (effective October 1, 1996; Central Valley Board, 1996a, d)	–	–	–	8,000	–	–
WY 1997-2001 San Luis Drain/Grassland Bypass Channel Project negotiated annual load targets for discharge through the San Luis Drain to the San Joaquin River (USBR, 1995)	93,400	–	–	5,661–6,660[a]	0.06-0.07/acre	–
WY 1997 San Luis Drain/Grassland Bypass Channel Project measured load discharged through the drain to the San Joaquin River (USBR and others, 1998)	97,400	37,483	62.5	6,960	0.073/acre 0.189/acre-ft	0.38
January 26, 1997 estimated load from Coast Range runoff discharged through the San Luis Drain (Grassland Area Farmers, 1997)	–	–	–	137	–	–
WY 1998 San Luis Drain/Grassland Bypass Channel Project measured load discharged through the San Luis Drain to the San Joaquin River (USBR and others, 1998 and ongoing)	97,400	45,858	66.9	9,118	0.094/acre 0.199/acre-ft	0.47
February, 1998 estimated load from Coast Range runoff discharged through the San Luis Drain (Grassland Area Farmers, 1997)	–	–	–	487	–	–

[a] Note: Negotiated annual load targets (6,600 lbs selenium) differs from a total of monthly load targets (7,096 lbs selenium).

1998a) has essentially removed these channels as possible alternative flow paths for drainage water. This regulation also will make it difficult to reuse the wetland channels as alternative channels during flood runoff or in the event that Westlands Water District once again uses the San Luis Drain.

Tables B9 and B10 give detailed monthly data for the Grassland Bypass Channel Project including volumes, targets, loads, and concentrations (USBR and others, 1998 and ongoing). The annual load of 7,104 for WY 1997 includes 6,960 lbs selenium that was discharged from the San Luis Drain to the San Joaquin River and 137 lbs selenium that was discharged to wetland channels during a flood in January 1997. A fee of $60,000 was paid by the Grassland Area Farmers for exceedances of monthly and annual selenium load targets by 437 lbs (6.6 percent) in the first year of the project. The annual load represents 0.073 lbs selenium per acre or 0.189 lbs selenium per acre-ft for the Grassland Area of 97,400 acres. The average selenium concentration for WY 1997 was 62.5 µg/L and the total volume was 37,483 acre-ft. The annual load for the second year of the Grassland Bypass Channel Project, WY 1998, was 9,130 lbs selenium. The annual selenium load target was exceeded by 37 percent which could have incurred a fee of $174,400, if the load was left unadjusted for flooding during the higher than normal rainfall in 1998 (note, 1998 was an El Nino year). The WY 1998 flood load was estimated at 487 lbs selenium, with 350 lbs documented in overflow to wetland channels. The average selenium concentration for the discharge for WY 1998 was 67 µg/L and the total volume was 45,858 acre-ft. This annual selenium load represents 0.094 lbs selenium per acre or 0.199 lbs selenium per acre-feet for the Grassland Area.

Table B9. Grassland Bypass Channel Project (reuse of a 28-mile portion of the San Luis Drain) WY 1997 drainage, selenium concentrations, selenium loads, and selenium load targets for regulatory purposes.

[Data source: USBR and others, 1998 and ongoing]

WY 1997	Drainage (average monthly acre-ft)	Selenium (average monthly µg/L)	Selenium load (average monthly lbs)	Negotiated selenium load targets (lbs)	Incentive fee (dollars)
Sept. 23–30, 1996	–	–	55[a]	–	–
October 1996	1,274	60.8 (58.6)	202	348	$0
November 1996	1,566	58.3	252	348	$0
December 1996	1,943	51.5	285	389	$0
January 1997	3,696	59.5	599[b]	533	$2,800
February 1997	4,166	76.6	878[b]	866	$700
March 1997	4,867	84.2	1,119	1,066	$700
April 1997	4,446	105.5	1,280	799	$2,800
May 1997	4,208	75.7	849	666	$2,800
June 1997	3,451	64.3	611	599	$700
July 1997	3,271	48.1	428	599	$0
August 1997	3,153	40.6	348	533	$0
September 1997	1,442	25.3	109	350	$0
TOTAL (monthly)	37,483	–	6,960	7,096 (monthly)	$10,500
TOTAL (yearly)	37,483	62.5 (average)	6,960	6,660 (yearly)	$50,000
Storm discharge (lower watershed, Agatha Canal)	–	–	137[b]	–	–
TOTAL (project plus storm discharge)	–	–	7,097	–	$60,500

[a] Estimated and not counted in total.

[b] 89 lbs selenium in January and 48 lbs selenium in February discharged to wetland sloughs (Agatha Canal) during San Luis Drain overflow events due to storms in January and February, 1997.

Table B10. Grassland Bypass Channel Project (reuse of a 28-mile portion of the San Luis Drain) WY 1998 drainage, selenium concentrations, selenium loads, and selenium load targets for regulatory purposes.

[Data source: USBR and others, 1998 and ongoing]

WY 1998	Drainage (average monthly acre-ft)	Selenium (average monthly µg/L)	Selenium load (average monthly lbs)	Negotiated selenium load targets (lbs)	Incentive fee (dollars)
October 1997	1,753	51.9	248	348	$0
November 1997	1,555	48.9	207	348	$0
December 1997	1,403	48.7	178	389	$0
January 1998	1,419	85.0	335	533	$0
February 1998	6,980	52.5	965[a]	866	$4,200[b]
March 1998	7,094	83.3	1,600	1,066	$4,200[b]
April 1998	5,517	105.4	1,554 (1,560)	799	$4,200[b]
May 1998	4,881	104.5	1,371	666	$4,200[b]
June 1998	3,629	82.1	807	599	$4,200[b]
July 1998	4,564	49.7	615	599	$1,200
August 1998	3,876	47.5	500	533	$0
September 1998	3,187	43.1	388	350	$2,200
TOTAL (monthly)	45,858	–	–	7,096 (monthly)	–
TOTAL (yearly)	45,858	66.9 (average)	8,768	6,660 (yearly)	$150,000[b]
Storm discharge (lower watershed, Agatha Canal))	–	–	350[a]	–	–
TOTAL (project plus storm discharge)	–	–	9,118	–	$174,400 ($3,400 paid)

[a] 350 lbs selenium discharged to wetland sloughs (Agatha Canal) during San Luis Drain overflow events due to storms in February, 1998.

[b] Fees waived because of above average rainfall for WY 1998.

Westlands Subarea in Combination with Grassland Subarea

An analysis of discharge by the USBR in 1983 included the San Luis Unit and Delta-Mendota Services Areas, which encompasses both the Grassland and Westlands subareas. Taking a potential worst-case scenario for the year 2020, the amount of drainage from the San Luis Unit Service Area is 135,240 acre-ft and from the Delta-Mendota Service Area is 65,783 acre-ft. Using assigned selenium concentrations of 50, 150, and 300 µg/L applied to these amounts of drainage, the range of selenium loads from San Luis Unit Service Area is from 18,393 to 110,356 lbs per year; and for the Delta-Mendota Service Area is from 8,946 to 53,679 lbs per year. The range of combined selenium loads is from 27,339 to 164,035 lbs per year.

Evidentiary hearings (Westlands Water District, 1996) included a scenario in which the Grassland Area drainage discharged to the San Joaquin River would be discharged to the San Luis Drain, along with the Westlands Water District discharges. However, under current agreements, the Grassland Bypass Channel Project would terminate if Westlands Water District is given permission to use the San Luis Drain (USBR, 1995). Additional drainage from the Grassland Area (30,000 to 40,000 acre-ft) is hypothesized here to be of better quality than that of water discharged to Kesterson Reservoir. Using a measured WY-1997 average concentration of 62.5 µg/L applied to these volumes, the projected selenium load is 5,100 to 6,800 lbs per year (table B2). Under a combined Grassland/Westlands scenario, the range of total annual loads is 13,518 to 15,273 lbs per year selenium, if Westlands Water District drainage contains a concentration of 50 µg/L selenium. Total annual loads increase to 30,355 to 32,218 lbs selenium if Westlands Water District drainage contains a concentration of 150 µg/L; and 55,610 to 57,637 lbs per year if Westlands Water District drainage contains a concentration of 300 µg/L.

Projections from Drainage Program Management Options

Data for acreage and drainage volumes for each of the five subareas used by the Drainage Program for planning purposes is given in tables B11 through B17. Two possible alternative *futures* were defined by the Drainage Program: (1) no implementation of a management plan, 0.60 to 0.75 acre-ft per acre per year generated drainage, namely, *without future*; and (2) with implementation of a management plan, 0.40 acre-ft per acre per year generated drainage, namely, *with future* (Drainage Program 1989 and 1990a). A third condition defined here is called *with targeted future*. The *targeted future* condition applies a factor of 0.20 acre-ft per acre per year of generated drainage, exemplifying the lowest, although probably not realistic, irrigation water return. Like earlier plans, the Drainage Program did not calculate concentrations of selenium in drainage water or selenium loads directly, but rather focused on estimating the volume of drainage and the affected acreage for subareas. Assigning selenium concentrations of 50, 150, and 300 µg/L to these volumes, gives the general magnitude of expected selenium loads.

Table B18 gives selenium load details from each of the five subareas based on estimates given by the Drainage Program for year 2000 and assigned selenium concentrations of 50, 150, and 300 µg/L. This summary gives ranges of acre-feet of drainage and projected annual loads of selenium using assigned concentrations. Figures B1a, b, and c depict the ranges of agricultural loads for assigned selenium concentrations of 50, 150, and 300 µg/L, if all subareas are considered discharging to a valleywide drain. Considered on a subarea basis, the selenium loads are (table B18):

- **Northern subarea.** Discharge from the Northern subarea is to the San Joaquin River. The range of projections of annual selenium loads from the Northern subarea is 925 to 3,536 lbs selenium using an assigned concentration of 50 µg/L; 2,774 to 10,608 lbs per year using an assigned concentration of 150 µg/L; and 5,549 to 21,216 lbs per year using an assigned concentration of 300 µg/L.

- **Grassland subarea.** Discharge from the Grassland subarea is to the San Joaquin River. The range of projections of annual selenium loads from the Grassland subarea is 2,938 to 11,696 lbs per year using an assigned concentration of 50 µg/L; 8,813 to 35,088 lbs per year using an assigned concentration of 150 µg/L; and 17,626 to 70,176 lbs per year using an assigned concentration of 300 µg/L.

- **Westlands subarea.** Westlands Water District (encompassing the Westlands subarea) is currently asking to extend the San Luis Drain to the Bay-Delta as a drainage outlet. The range of projections of annual selenium loads from the Westlands subarea is 1,877 to 11,016 lb per year using an assigned concentration of 50 µg/L; 5,630 to 33,048 lb per year using an assigned concentration of 150 µg/L; and 11,261 to 66,096 lb per year using an assigned concentration of 300 µg/L.

- **Tulare subarea.** Tulare subarea currently discharges to privately owned evaporation ponds. The range of projections of annual selenium loads from the Tulare subarea is 2,611 to 10,200 lbs per year using an assigned concentration of 50 µg/L; 7,834 to 30,600 lbs per year using an assigned concentration of 150 µg/L; and 15,667 to 61,200 lbs per year using an assigned concentration of 300 µg/L selenium.

- **Kern subarea.** Kern subarea currently discharges to privately owned evaporation ponds. The range of projections of annual selenium loads from the Kern subarea is 1,088 to 6,256 lbs per year using an assigned concentration of 50 µg/L; 3,264 to 18,768 lbs per year using an assigned concentration of 150 µg/L; and 6,528 to 37,536 lbs per year using an assigned concentration of 300 µg/L.

Projections from Currently Available Data

Tables B1, B2, B9, B10, B19, B20, and B21 give the derivation and details of specific loads projected here for each subarea based on a compilation of currently available data for problem acreage, drainage volume, and selenium concentration. These data have become available since the Drainage Program was completed in 1990. Depending on the type of data available from each subarea, projections are made regarding concentration and load. Because of limited data and broad ranges of management alternatives across the subareas, maximum and minimum selenium concentrations are given to bracket possible load scenarios using specific volumes of drainage for each subarea. Although site-specific in nature, these projections address only the present discharge to manage the annual imbalance, and not general amounts of *problem water*. Projections for the five subareas are:

- **Northern subarea.** Discharge from the Northern subarea is to the San Joaquin River. The projected selenium concentration range is 5 to 10 µg/L for the Northern subarea. The Northern subarea minimum projection is based on a nominal 5 µg/L selenium concentration applied to adhere to a 5 µg/L USEPA criterion for the San Joaquin River. Because management options were not recommended for the Northern subarea, the assumed drainage volume is that estimated by the Drainage Program for year 2000 without implementation of a management plan (Drainage Program, 1990a) (tables B13 through B17). The range of projected annual selenium loads for the Northern subarea is 350 to 750 lbs per year, if a maximum concentration of 10 µg/L is applied to the same drainage volume.

- **Grassland subarea.** Discharge from the Grassland subarea is to the San Joaquin River. The projected selenium concentration range is 68 to 152 µg/L for the Grassland subarea. The Grassland subarea projection is based on the Grassland Bypass Channel Project measured volume of discharge in WY 1997 (tables B9 and B10). The projected Grassland subarea minimum load is 6,960 lbs per year. The projected Grassland maximum load is 15,500 lbs per year, a load similar to that measured for the San Joaquin River at Crows Landing in an extremely wet year (WY 1998). The maximum load attempts to represent a load that includes upstream San Joaquin River loads of selenium and recycled selenium loads from the Delta-Mendota Canal.

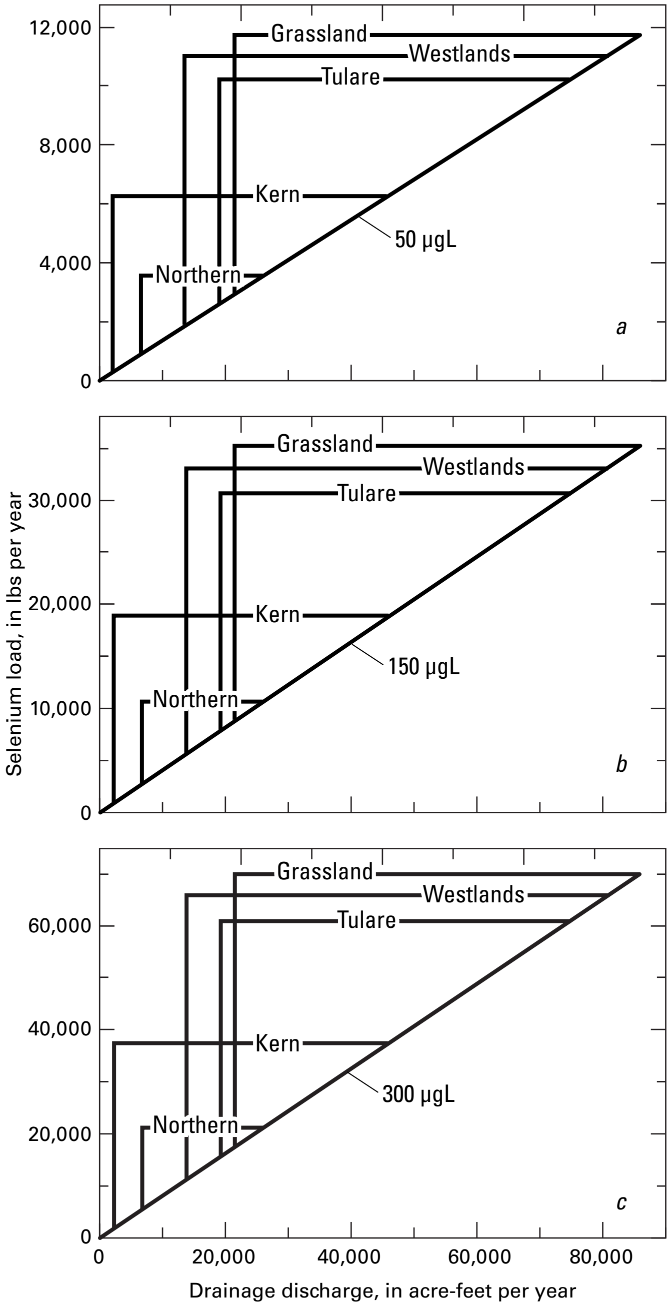


Figure B1. Annual selenium load projections at (*a*) 50, (*b*) 150 and (*c*) 300 µg/L selenium for drainage discharges from the Northern, Grassland, Westlands, Tulare, and Kern subareas.

Table B11. Acreage used by the Drainage Program for planning purposes in 1985 –1990 (Drainage Program 1989, Table 1–1).

Subarea	Total acreage (acres)	Irrigable acreage[a] (acres)	Irrigated acreage[a] (acres)	Drained acreage (acres)
Northern	236,000	165,000	157,000	26,000
Grassland[a]	707,000	345,000	311,000[b]	51,000
Westlands	770,000	640,000	576,000	5,000
Tulare	883,000	562,000	506,000[b]	42,000
Kern	1,210,000	762,000	686,000	11,000
Total	3,806,000	2,474,000	2,235,000	135,000

[a] A factor of 90 to 95 percent was used to calculate irrigated acres from irrigable acres (Drainage Program, 1990a, Table 11).

[b] Estimates differ from 1989 to 1990 (Drainage Program, 1990a, Table 11, Grassland subarea 329,000 acres; Tulare subarea 551,000 acres).

- **Westlands subarea.** Westlands subarea (or Westlands Water District) currently recycles its drainage and therefore no discharge data is available. The projected selenium concentration range is 49 to 150 µg/L for the Westlands subarea (note, no current data, only testimony on acreage is available). The Westlands Water District subarea minimum acre-feet discharge and load are for conditions presented as evidence for Westlands Water District (60,000 acre-ft at 49 µg/L selenium, Westlands Water District, 1996) (tables B1 and B2). The maximum load is based on a selenium concentration of 150 µg/L (163 µg/L median and a USBR conservative estimate of at least 150 µg/L) applied to 60,000 acre-ft. The projected range of annual selenium loads for Westlands Water District is 8,000 to 24,480 lbs per year.
- **Tulare subarea.** Tulare subarea currently discharges to privately owned evaporation ponds. The Tulare subarea projections are based on measurements for volume and selenium concentration from 1993 to1997 (Anthony Toto, Central Valley Board, personal commun., January, 1998,). A compilation of available data from discharges in the Tulare subarea is given in tables B19 and B20. Concentration and volume data for 1988, 1989, 1994, and 1996 are shown for comparison, although sets of data are not available in order to calculate load. An average volume is used in the projections in conjunction with the minimum and maximum selenium loads. From the sparse data available from the Tulare subarea for 1993, 1995, and 1997,

Table B12. Acreage (irrigated, abandoned, and problem), *problem water*, and annualized cost (problem water reduction and management plan implementation) used by the Drainage Program (1990a).

[The *without future* alternative (no implementation of a management plan) includes abandonment of lands due to salinization.]

Subarea	Irrigated acreage for 1990[a] (acres)	Irrigated acreage *without future* for 2000[a] (acres)	Abandoned acreage *without future* for 2000[a] (acres)	Problem acreage *without future* for 2000[b] (acres)	Factor (problem water generation[c]) (acre-ft/acre)	*Problem water* generated by 2000[d] (acre-ft)	*Problem water* generated by 2040[d] (acre-ft)	Annualized cost/acre for problem water reduction[e] (dollars)	Annualized cost for management plan implementation[e] (dollars)
Northern	157,000	152,000	0	34,000	0.70 – 0.75	26,000	38,000	–	–
Grassland[f]	329,000	325,000	0	116,000	0.70 – 0.75	86,000	155,000	$107	$12,412,000
Westlands	576,000	551,000	28,000	108,000	0.60	81,000	153,000	$136	$14,688,000
Tulare	551,000	517,000	38,000	125,000	0.70 – 0.75	75,000	209,000	$104	$13,000,000
Kern	686,000	665,000	18,000	61,000	0.71	46,000	111,000	$137	$ 8,357,000
Total	2,299,000	2,210,000	84,000	444,000	–	314,000	666,000	–	$48,457,000

[a] Drainage Program (1990a), table 11.

[b] Drainage Program (1990a), table 9.

[c] Drainage Program (1990a) page 76.

[d] Drainage Program (1990a) table 10.

[e] A 50-year planning period and problem acreage for 2000 were used (Drainage Program, 1990a: pages 5, 143, 148, 153, and 156; approximately $42,000,000, page 5). Cost/acre includes the cost of fish and wildlife components.

[f] The Grassland subarea total acreage is 707,000 with 329,000 irrigated acres (90% of irrigable lands). The Grassland Area/Drainage Problem Area within the subarea is approximately 100,000 acres.

Table B13. Projected drainage using Drainage Program (1990a) tile-drained acreage for 1990, 2000, and 2040.

[No drainage improvement is considered as 0.75 acre-ft/acre/year and minimal improvement is considered as 0.55 acre-ft/acre/year. The *without future* (no implementation of a management plan) includes abandonment of lands due to salinization. An additional calculation is made for the Westlands subarea based on upslope contributions from non-tile drained acreage to tile-drained acreage (State Board, 1985).]

Subarea	Tile-drained acreage for 1990[a] (acres)	Factor (acre-ft/ acre/year)	Drainage for 1990[b] (acre-ft)	Tile-drained acreage *without future* for 2000[a] (acres)	Factor (acre-ft/ acre/year)	Drainage *without future* for 2000[b] (acre-ft)	Tile-drained acreage *without future* for 2040[a] (acres)	Factor (acre-ft/ acre/ year)	Drainage *without future* for 2040[b] (acre-ft)
Northern	24,000	0.75	18,000	34,000	–[c]	26,000	51,000	0.75	38,000[d]
Grassland	50,000	0.75	38,000	85,000	–[c]	54,000	152,000	0.55	84,000[d]
Westlands	5,000	0.75	4,000	50,000	–[c]	28,000	49,000	0.55	27,000
Westlands	42,000[e]	0.75	31,500[e]	–	–[c]	–	–	–	–
Tulare	43,000	0.60	32,000	86,000	–[c]	47,000	94,000	0.55	52,000
Kern	11,000	0.75	8,000	14,000	–[c]	8,000	40,000	0.55	22,000
Total	133,000	–	100,000	269,000	–[c]	163,000	386,000	–	223,000

[a] Drainage Program (1990a), table 11.

[b] Drainage Program (1990a), table 13.

[c] No factor given in table 13 (Drainage Program, 1990a)

[d] Table 13 shows 37,000 and 105,000 acre-ft (Drainage Program, 1990a).

[e] Not included in total.

Table B14. Projected drainage using a drainage improvement factor of 0.40 acre-ft/acre/year and Drainage Program (1990a) data.

[The *with future* alternative specifies implementation of a management plan (Drainage Program, 1990a). An additional calculation is made for Westlands based on upslope contributions from non-tile drained acreage to tile drained acreage (State Board, 1985).]

Subarea	Tile-drained acreage for 1990[a] (acres)	Factor[b] (acre-ft/acre/year)	Projected drainage with future for 1990 (acre-ft)	Tile-drained acreage with future for 2000[a] (acres)	Factor[b] (acre-ft/acre/year)	Projected drainage *with future* for 2000 (acre-ft)	Tile-drained acreage *with future* for 2040[a] (acres)	Factor[b] (acre-ft/acre/year)	Projected drainage *with future* for 2040 (acre-ft)
Northern[c]	24,000	0.40	9,600	34,000	0.40	13,600	44,000	0.40	17,600
Grassland	50,000	0.40	20,000	108,000	0.40	43,200	192,000	0.40	76,800
Westlands	5,000	0.40	2,000	69,000	0.40	27,600	140,000	0.40	56,000
Westlands	42,000[d]	0.40	16,800[d]	–	–	–	–	–	–
Tulare	43,000	0.40	17,200	96,000	0.40	38,400	277,000	0.40	110,800
Kern	11,000	0.40	4,400	53,000	0.40	21,200	106,000	0.40	42,400
Total	133,000	–	53,200	360,000	–	144,000	759,000	–	303,600

[a] Drainage Program (1990a), table 27.

[b] Factor applied from table 26 (Drainage Program, 1990a).

[c] No management plan recommended for Northern subarea (Drainage Program, 1990a).

[d] Not included in total.

the projected selenium concentration range is 1.7 to 9.8 µg/L. The range of projected annual loads for the Tulare subarea is 91 lbs to 519 lbs per year, with the majority of the discharge to the Tulare Lake Drainage District ponds. A main point of these calculations is to compare the magnitude of loading from subareas even in view of limited data. The projected annual selenium load from this area is small relative to that projected from Westlands Water District and Grassland subarea, largely because the projected selenium concentrations are relatively low in managed drainage from the Tulare subarea.

- **Kern subarea.** Kern subarea currently discharges to privately owned evaporation ponds. A compilation of available data from discharges in the Kern subarea is given in table B21. Kern subarea projections are based on measurements for volume and selenium concentration from 1993 to 1997 (Anthony Toto, Central Valley Board, personal commun., January, 1998). An average volume is used in the projections in conjunction with minimum and maximum selenium loads. From the sparse data available, the projected selenium concentration range is 175 to 254 µg /L for Kern subarea. Projected annual selenium loads from the Kern subarea range from a total of 1,089 to 1,586 lbs. A main point of these calculations is to compare the magnitude of loading from subareas even in view of limited data. The projected annual selenium load from this area is small relative to that from Westlands Water District and Grassland subarea, largely because the projected volumes of drainage are relatively low.

A selenium load summary based on the currently available data compiled here is shown in table 7. In addition, sets of graphs in figures B2 and B3 compare generalized projections from Drainage Project volumes (table B18) with those based on currently available data. Ranges of drainage volume and annual selenium loads are presented for each assigned concentration, specifically, 50, 150, and 300 µg/L for each subarea (figs. B2a to e). Ranges of projected drainage volumes and annual selenium loads are presented for minimum and maximum concentrations derived from current data (figs. B3a to e). In general, these graphical techniques enable a prediction or projection of an annual selenium load for any assigned concentration or current condition given a specific drainage volume. Again, the ranges are due to varying estimates of predicted *problem water* and subsurface drainage under different management alternatives. The comparisons show the relative contribution of load from each subarea in the event that all subareas discharge to a proposed San Luis Drain extension. The graphical technique also shows patterns of selenium concentration and load that are indicative of the geology, hydrology, and chosen management options for each subarea.

Table B15a. Projections of annual selenium loads per subarea using Drainage Program *problem water* estimates for 2000 (*without future* alternative, 0.60 to 0.75 acre-ft/acre/year) and a 50 µg/L selenium concentration in drainage.

[Data source: Drainage Program, 1990a.]

Subarea	Problem acreage for 2000[a] (acres)	Factor (problem water generation acre-ft/acre/year)[b]	*Problem water* for 2000[c] (acre-ft)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Factor (lbs/acre)	Factor (lbs/acre-ft)
Northern	34,000	0.70–0.75	26,000	50	3,536	0.1	0.136
Grassland	116,000	0.70–0.75	86,000	50	11,696	0.1	0.136
Westlands	108,000	0.70–0.75	81,000	50	11,016	0.1	0.136
Tulare	125,000	0.60	75,000	50	10,200	0.08	0.136
Kern	61,000	0.70–0.75	46,000	50	6,256	0.1	0.136
TOTAL	444,000	0.71	314,000	50	42,704	0.096	0.136

Table B15b. Projections of annual selenium loads per subarea using Drainage Program *problem water* estimates for 2000 (*without future* alternative, 0.60 to 0.75 acre-ft/acre/year) and a 150 µg/L selenium concentration in drainage.

[Data source: Drainage Program, 1990a.]

Subarea	Problem acreage for 2000[a] (acres)	Factor (problem water generation acre-ft/acre/year)[b]	*Problem water* for 2000[c] (acre-ft)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Factor (lbs/acre)	Factor (lbs/acre-ft)
Northern	34,000	0.70 – 0.75	26,000	150	10,608	0.31	0.408
Grassland	116,000	0.70 – 0.75	86,000	150	35,088	0.31	0.408
Westlands	108,000	0.70 – 0.75	81,000	150	33,048	0.31	0.408
Tulare	125,000	0.60	75,000	150	30,600	0.24	0.408
Kern	61,000	0.70 – 0.75	46,000	150	18,768	0.31	0.408
TOTAL	444,000	0.71	314,000	150	128,112	0.29	0.408

Table B15c. Projections of annual selenium loads per subarea using Drainage Program *problem water* estimates for 2000 (*without future* alternative, 0.60 to 0.75 acre-ft/acre/year) and a 300 µg/L selenium concentration in drainage.

[Data source: Drainage Program, 1990a.]

Subarea	Problem acreage for 2000[a] (acres)	Factor (problem water generation acre-ft/acre/year)[b]	*Problem water* for 2000[c] (acre-ft)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Factor (lbs/acre)	Factor (lbs/acre-ft)
Northern	34,000	0.70 – 0.75	26,000	300	21,216	0.31	0.816
Grassland	116,000	0.70 – 0.75	86,000	300	70,176	0.31	0.816
Westlands	108,000	0.70 – 0.75	81,000	300	66,096	0.31	0.816
Tulare	125,000	0.60	75,000	300	61,200	0.24	0.816
Kern	61,000	0.70 – 0.75	46,000	300	37,536	0.31	0.816
TOTAL	444,000	0.71	314,000	300	256,224	0.29	0.816

[a] Drainage Program (1990a), table 9.

[b] Drainage Program (1990a), page 76.

[c] Drainage Program (1990a), table 10.

Table B16a. Projections of annual selenium loads per subarea using Drainage Program *subsurface drainage volumes* for 2000 (*without future* alternative, 0.60 to 0.75 acre-ft/acre/year) and selenium concentrations of 50, 150, and 300 µg/L.

[Data source: Drainage Program, 1990a.]

Subarea	Drained acreage *without future*[a] (acres)	Subsurface drainage for 2000 *without future*[b] (acre-ft)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)
Northern	34,000	26,000	50	3,536	150	10,608	300	21,216
Grassland	85,000	54,000	50	7,344	150	22,032	300	44,064
Westlands	50,000	28,000	50	3,808	150	11,424	300	22,848
Tulare	86,000	47,000	50	6,392	150	19,176	300	38,352
Kern	14,000	8,000	50	1,088	150	3,264	300	6,528
TOTAL	269,000	163,000	50	22,168	150	66,504	300	133,008

Table B16b. Projections of annual selenium loading per subarea using Drainage Program *subsurface drainage volumes* for 2000 (*with future* alternative, 0.40 acre-ft/acre/year) and selenium concentrations of 50, 150, and 300 µg/L.

[Data source: Drainage Program, 1990a.]

Subarea	Drained acreage *with future*[a] (acres)	Subsurface drainage for 2000 *with future*[b] (acre-ft)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)
Northern	34,000	13,600	50	1,850	150	5,549	300	11,098
Grassland	108,000	43,200	50	5,875	150	17,625	300	35,251
Westlands	69,000	27,600	50	3,754	150	11,261	300	22,522
Tulare	96,000	38,400	50	5,222	150	15,667	300	31,334
Kern	53,000	21,200	50	2,883	150	8,650	300	17,299
TOTAL	360,000	144,000	50	19,584	150	58,752	300	117,504

Table B16c. Projections of annual selenium loading per subarea for 2000 using Drainage Program *subsurface drainage volumes*, *with targeted future* alternative (0.20 acre-ft/acre/year), and selenium concentrations of 50, 150, and 300 µg/L.

[Data source: Drainage Program, 1990a.]

Subarea	Drained acreage *with targeted future*[a] (acres)	Subsurface drainage for 2000 *with targeted future*[c] (acre-ft)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)	Projected selenium (µg/L)	Projected selenium load (lbs/year)
Northern	34,000	6,800	50	925	150	2,774	300	5,549
Grassland	108,000	21,600	50	2,938	150	8,813	300	17,626
Westlands	69,000	13,800	50	1,877	150	5,630	300	11,261
Tulare	96,000	19,200	50	2,611	150	7,834	300	15,667
Kern	53,000	10,600	50	1,442	150	4,325	300	8,650
TOTAL	360,000	72,000	50	9,793	150	29,376	300	58,753

[a] Drainage Program (1990a), table 11.

[b] Drainage Program (1990a), table 13.

[c] Applied factor of 0.20 acre-ft/acre (see text).

Table B17. Projections of annual selenium loads per subarea using Drainage Program drainage estimates (subsurface drainage, *problem water*, drainage *without future*, drainage *with future*, and drainage with a *targeted future)* and selenium concentrations of 50, 150, and 300 µg/L.

[In the *targeted future* projection, a factor of 0.2 acre-ft/acre/year is applied. Se, selenium. Data source: Drainage Program, 1990a.]

Subarea	Subsurface drainage for 1990			Projected *problem water* for 2000[a]			Projected drainage for 2000 *without future*[b]			Projected drainage for 2000 *with future*[c]			Projected drainage with *targeted future*[d]		
	(acre-ft/ year)	(µg /L Se)	Se loads (lbs/ year)	(acre-ft/ year)	(µg /L Se)	Se loads (lbs/year)	(acre-ft/ year)	(µg /L Se)	Se loads (lbs/year)	(acre-ft/ year)	(µg /L Se)	Se loads (lbs/year)	(acre-ft/ year)	(µg /L Se)	Se loads (lbs/year)
Northern	18,000	50	2,448	26,000	50	3,536	26,000	50	3,536	13,600	50	1,850	6,800	50	925
Grassland	38,000	50	5,168	86,000	50	11,696	54,000	50	7,344	43,200	50	5,875	21,600	50	2,938
Westlands	4,000	50	544	81,000	50	11,016	28,000	50	3,808	27,600	50	3,754	13,800	50	1,877
Tulare	32,000	50	4,352	75,000	50	10,200	47,000	50	6,392	38,400	50	5,222	19,200	50	2,611
Kern	8,000	50	1,088	46,000	50	6,256	8,000	50	1,088	21,200	50	2,883	10,600	50	1,442
TOTAL	100,000	–	13,600	314,000	–	42,704	163,000	–	22,168	144,000	–	19,584	72,000	–	9,793
Northern	18,000	150	7,344	26,000	150	10,608	26,000	150	10,608	13,600	150	5,549	6,800	150	2,774
Grassland	38,000	150	15,504	86,000	150	35,088	54,000	150	22,032	43,200	150	17,625	21,600	150	8,813
Westlands	4,000	150	1,632	81,000	150	33,048	28,000	150	11,424	27,600	150	11,260	13,800	150	5,630
Tulare	32,000	150	13,056	75,000	150	30,600	47,000	150	19,176	38,400	150	15,667	19,200	150	7,834
Kern	8,000	150	3,264	46,000	150	18,768	8,000	150	3,264	21,200	150	8,650	10,600	150	4,325
TOTAL	100,000	–	40,800	314,000	–	128,112	163,000	–	66,504	144,000	–	58,751	72,000	–	29,376
Northern	18,000	300	14,688	26,000	300	21,216	26,000	300	21,216	13,600	300	11,098	6,800	300	5,549
Grassland	38,000	300	31,008	86,000	300	70.176	54,000	300	44,064	43,200	300	35,251	21,600	300	17,626
Westlands	4,000	300	3,264	81,000	300	66,096	28,000	300	22,848	27,600	300	22,522	13,800	300	11,261
Tulare	32,000	300	26,112	75,000	300	61,200	47,000	300	38,352	38,400	300	31,334	19,200	300	15,667
Kern	8,000	300	6.528	46,000	300	37,536	8,000	300	6,528	21,200	300	17,299	10,600	300	8,650
TOTAL	100,000	–	81,600	314,000	–	256,224	163,000	–	133,008	144,000	–	117,504	72,000	–	58,753

[a] Drainage Program (1990a), table 10.

[b] Drainage Program (1990a), table 13.

[c] See calculation this report, Table B14. In general, see tables 27 and 26 for acreage and factors, respectively (Drainage Program, 1990a).

[d] See this report, Table B15.

Table B18. Summary of projections of annual selenium loads per subarea using Drainage Program (1990a) estimates of drainage volume and different assigned selenium concentrations (50, 150, 300 µg/L).

[Total drainage/year from all subareas is from 69,400 to 314,000 acre-ft. Data source: Drainage Program, 1990a.]

Subarea drainage (acre-ft/year)	Selenium load (lbs/year)		
	50 µg/L[a]	150 µg/L[b]	300 µg/L[c]
Northern 6,800	925	2,774	5,549
Northern 13,600	1,850	5,549	11,098
Northern 26,000	3,536	10,608	21,216
Grassland 21,600	2,938	8,813	17,626
Grassland 43,200	5,875	17,625	35,251
Grassland 54,000	7,344	22,032	44,064
Grassland 86,000	11,696	35,088	70,176
Westlands 13,800	1,877	5,630	11,261
Westlands 27,600	3,754	11,260	22,522
Westlands 28,000	3,808	11,424	22,848
Westlands 81,000	11,016	33,048	66,096
Tulare 8,400	2,611	7,834	15,667
Tulare 19,200	5,222	15,667	31,334
Tulare 47,000	6,392	19,176	38,382
Tulare 75,000	10,200	30,600	61,200
Kern 8,000	1,088	3,264	6,528
Kern 10,600	1,442	4,325	8,650
Kern 21,200	2,883	8,650	17,299
Kern 46,000	6,256	18,768	37,536
Total selenium load/year (all subareas)			
Minimum	9,439	28,315	56,631
Min w/o Northern	8,514	25,541	51,082
Maximum	42,704	128,112	256,224
Max w/o Northern	39,168	117,504	235,008

[a] Equivalent to 0.136 lbs selenium/acre-ft.

[b] Equivalent to 0.408 lbs selenium/acre-ft.

[c] Equivalent to 0.817 lbs selenium/acre-ft.

Table B19. Tulare subarea drainage and selenium concentrations in 1988 and 1989 for privately owned evaporation basins.

[Data sources: discharge, Anthony Toto, Central Valley Board, personal commun., January, 1998; selenium (Central Valley Board, 1990a).]

Evaporation basin or drainage district	Drainage (acre-ft/year)	Selenium (µg/L)	Selenium load (lbs/year)
1988			
Tulare Lake	14,294	–	(see text)
North	–	2.6	
Hacienda	–	–	
South	–	30	
Westlake	–	1–1.1	
Meyer	–	1	
Stone	–	1.6–4.3	
Britz	–	–	
Others	–	9.6–757	
1989			
Tulare Lake	13,705	–	(see text)
North	–	–	
Hacienda	–	2.0	
South	–	–	
Westlake	–	21	
Meyer	–	0.4–6.5	
Stone	–	0.8	
Britz	–	2.3–7.4	
Others	–	–	

Table B20. Tulare subarea drainage and selenium concentrations from 1993 to 1997 for privately owned evaporation basins.

[Data sources: discharge, Anthony Toto, Central Valley Board, personal commun., January, 1998; selenium (Central Valley Board, 1990a).]

Evaporation basin or drainage district	Drainage (acre-ft/year)	Selenium (µg/L)	Selenium load (lbs/year)
1993			
Subarea (total)	17,899–18,955	–	91–97
Tulare Lake	12,497 (net) (13,553)[a]	1.9 average	65–71
North	–	1.4	–
Hacienda	–	2.1	–
South	–	2.0	–
Westlake	4,309	1.3	15
Meyer	–	–	–
Stone	1,093	3.6	10.7
Britz	–	124	–
1994			
Subarea (total)	19,468	–	–
Tulare Lake	14,601	–	–
North	1,432	1.8	7.0
Hacienda	4,226	–	–
South	8,943	12.6	306
Westlake	3,478	1.2	11.6
Meyer	–	–	–
Stone	1,213	3.7	2.2
Britz	186	15–50	7.6–25.3
1995			
Subarea (total)	20,403	–	494–519
Tulare Lake	14,751	–	461
North	1,373	2.5	9.3
Hacienda	4,754	13.2	171
South	8,624	12.0	281
Westlake	3,478	2.25 average	21
Meyer	327	0.76	0.7
Stone	1,665	2.4	10.9
Britz	182	15–50	7.4–25
1996			
Subarea (total)	19,160	–	–
Tulare Lake	13,676	–	–
North	918	2.5	6.2
Hacienda	4,515	–	–
South	8,243	8.3	186
Westlake	5,152	–	–
Meyer	332	0.99	0.894
Stone	–	–	–
Britz	–	–	–
1997			
Subarea (total)	20,005		252–442
Tulare Lake	15,605	–	240–430
North	1,199	2.1/1.8[b]	6.8–5.9
Hacienda	5,238	–/5.9	84
South	9,168	13.6/6.0	339–150
Westlake	4,400	2.27 avg	12
Meyer	–	–	–
Stone	–	–	–
Britz	–	–	–

[a] Net = gross minus interceptor seepage.

[b] Two samplings for WY 1997 (June and September, 1997).

Table B21. Kern subarea drainage and selenium concentrations in 1988, 1989, and 1993 through 1997.

[Data sources: Anthony Toto, Central Valley Board, personal commun., January, 1998, except for selenium concentrations for 1988 and 1989 which are from Central Valley Board, 1990a).

Evaporation basin or drainage district	Drainage (acre-ft/year)	Selenium (µg/L)	Selenium load (lbs/year)
	1988		
Total	–	–	–
Lost Hills Water District	2,452	142	947
Rainbow Ranch	–	–	–
Lost Hills Ranch	–	2.4	–
	1989		
Total	–	–	–
Lost Hills Water District	3,831	83–671	865–6,992
Rainbow Ranch	–	212	–
Lost Hills Ranch	–	2.1	–
	1993		
Total	2,467	–	1,426
Lost Hills Water District	1,854	220	1,109
Rainbow Ranch	613	190	317
	1994		
Total	2,318	–	1,586
Lost Hills Water District	1,739	208	948
Rainbow Ranch	579	405	638
	1995		
Total	2,237	–	1,410
Lost Hills Water District	1,549	240	1011
Rainbow Ranch	688	213	399
	1996		
Total	2,365	–	1,407
Lost Hills Water District	1,501	238	972
Rainbow Ranch	864	185	435
	1997		
Total	2,072	–	1,089
Lost Hills Water District	1,620	195	859
Rainbow Ranch	452	187	230

Table B22. Selenium load scenarios using planned capacities of the San Luis Drain or valley-wide drain and assigned selenium concentrations of 50, 150, and 300 µg/L.

San Luis Drain design capacity	Selenium load (lbs/year)		
	50 µg/L	150 µg/L	300 µg/L
300 ft^3/s or 216,810 acre-ft/year (USBR, 1955) planned capacity Bakersfield to Mendota section	29,486	88,458	176,917
450 ft^3/s or 325,215 acre-ft/year (USBR, 1955) planned capacity Kesterson Reservoir to Bay/Delta section	44,229	132,688	265,375
144,200 acre-ft/year (USBR, 1955) initially needed	19,611	58,834	117,667
154,100 acre-ft/year maximum after 50 years (range 3,100 to 154,100 acre-ft/year (USBR, 1978)	20,958	62,873	125,746
201,025 acre-ft/year after 25 years (range 84,525 to 279,270 acre-ft/year (USBR, 1983)	27,339	82,018	164,036
60,000 to 100,000 acre-ft/year (Barcellos Judgment, 1986; USBR,1992)	8,160–13,600	24,480–40,800	48,960–81,600
60,000 acre-ft/year (Westlands Water District, 1996)	8,160	24,480	48,960
375,000 acre-ft/year (400,000-500,000 acre-ft/year needed capacity for drainage in San Francisco ocean out-fall, Montgomery Watson, 1993)	51,000	153,000	306,000

Table B23a. Projected selenium loads using Drainage Program (1990a) data (*problem water* and subsurface drainage) and daily fluxes from the western San Joaquin Valley to a proposed San Luis Drain extension.

[A selenium concentration of 50 µg/L selenium is hypothesized to be attainable with treatment. A selenium concentration of 150 µg/L is assigned to subsurface drainage.]

Drainage from all subareas (acre-ft)	Selenium load (lbs/year)	Selenium load (ksts[a]/year)	Selenium load (lbs/day)	Selenium (µg/L)	Factor (lbs/acre-ft)
314,000 (*problem water* at 50 µg/L selenium)	42,704	2.45	117	50	0.136
144,000–163,000 (subsurface drainage at 150 µg/L selenium)	58,752–66,504	3.4–3.8	161–182	150	0.408

Table B23b. Projected low-range selenium loads and daily fluxes from the western San Joaquin Valley to a San Luis Drain extension.

[See table 7 for derivation of selenium concentrations.]

Subareas	Selenium load (lbs/year)	Selenium load (ksts[a]/year)	Selenium load (lbs/day)	Selenium (µg/L)	Factor (lbs/acre-ft)
Northern	350	0.02	0.95	5	0.0135
Grassland	6,960	0.40	19	68	0.186
Westlands	8,000	0.46	22	49	0.133
Tulare	91	0.005	0.25	1.7	0.0047
Kern	1,089	0.062	3.0	175	0.475
Total	16,490	0.95	45.2	–	–

Table B23c. Projected high-range selenium loads and daily fluxes from the western San Joaquin Valley to a San Luis Drain extension.

[See table 7 for derivation of selenium concentrations.]

Subareas	Selenium load (lbs/year)	Selenium load (ksts[a]/year)	Selenium load (lbs/day)	Selenium (µg/L)	Factor (lbs/acre-ft)
Northern	700	0.04	1.9	10	0.027
Grassland	15,500	0.89	42	152	0.414
Westlands	24,480	1.4	67	150	0.408
Tulare	519	0.03	1.4	9.8	0.0266
Kern	1,586	0.09	4.3	254	0.692
Total	42,785	2.46	117	–	–

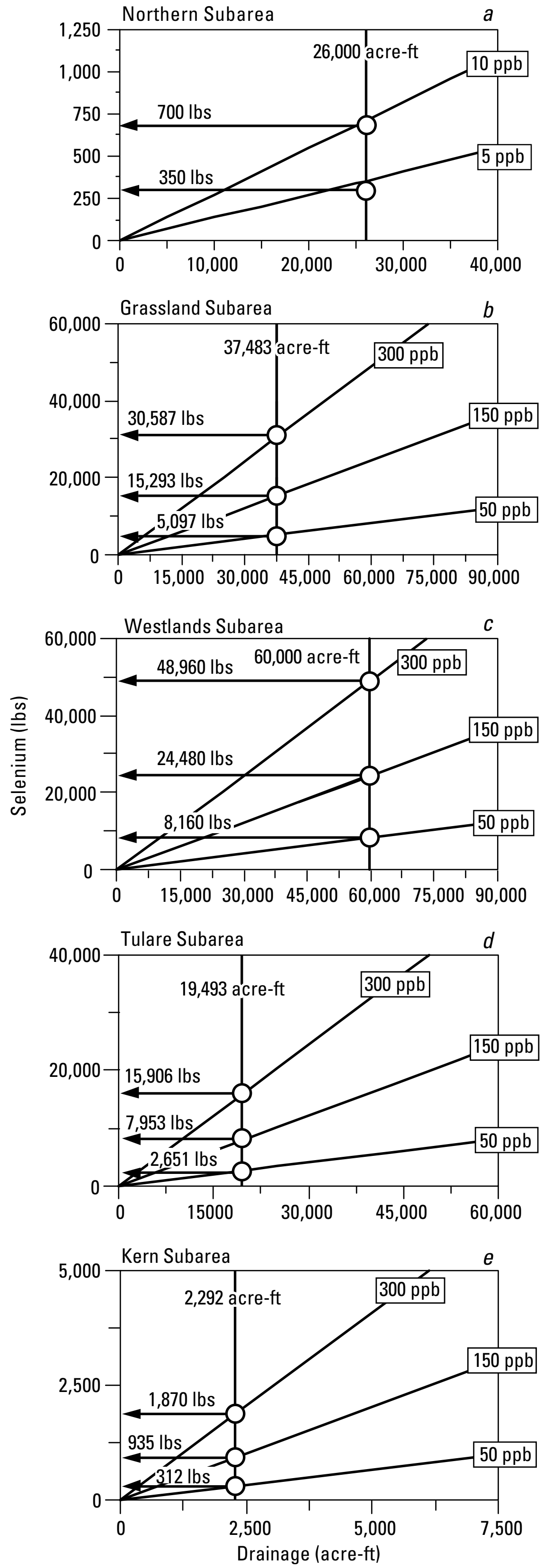
[a] One kesterson (kst) = 17,400 lbs selenium.

Estimates of Capacity of Drainage Conveyance (proposed San Luis Drain extension)

As a final check of the magnitude of the load projections, various design capacities of the San Luis Drain or a drain extension are combined with assigned selenium concentrations to calculate load (table B22). The concentration is held constant to simulate a constant discharge from a constructed conveyance system as opposed to a seasonally impacted conveyance system such as the San Joaquin River. The San Luis Drain design capacity is assumed to be 300 ft^3/s (as suggested as early as 1955 and recently), which is equivalent to 216,810 acre-ft per year (USBR, 1955, 1962, 1978; State Board, 1999a). At a selenium concentration of 50 µg/L, the annual projected selenium load is 29,486 lbs. Using an assigned concentration of 150 µg/L, the annual projected load is 88,458 lbs. For a 300 µg/L discharge, the annual projected load is 176,917 lbs. Other historical estimates of annual discharge for the San Luis Drain (for example, 144,200 acre-ft per year in early planning; 150,000 estimated during 1975–77 for 50 to 100 years of drainage; and 84,525 to 279,270 acre-ft estimated in 1983 for the period 1995–2095) also can be used to estimate loads by applying assigned concentrations to discharge capacity. An estimate used in the 1990s of drainage available from the San Joaquin Valley for discharge to a proposed San Francisco ocean outfall, which was a part of recycling efforts to meet water-quality objectives, showed a 375,000 acre-ft annual drainage discharge and a 400,000 to 500,000 acre-ft capacity drainage facility (Montgomery-Watson, 1993). Hence, most estimates show a need for a drain of greater than 200,000 acre-ft per year.

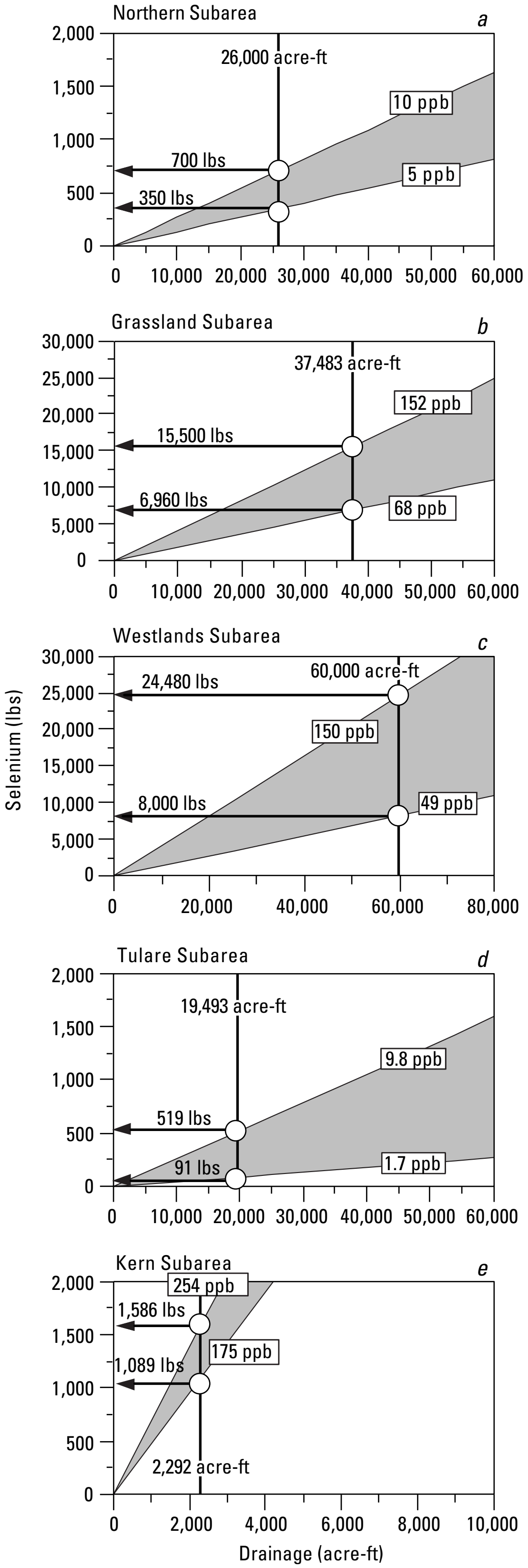
Total flux from Agricultural Drainage Discharge (lbs selenium per day)

It is also useful to present here projected selenium loads from the western San Joaquin Valley to the Bay-Delta in terms of rates (lbs selenium per year and lbs selenium per day) and in terms of cumulative load expressed in kestersons (ksts) (Presser and Piper, 1998). The kst unit is the cumulative total of 17,400 lbs selenium, which when released directly into Kesterson Reservoir caused ecotoxicity and visible ecological damage. It is used here as a measure of potential ecological damage based on selenium load. Table B23a shows the range of projected selenium loads (2.4 to 3.8 ksts per year) from the Valley through a San Luis Drain extension based on generalized Drainage Program data (314,000 acre-ft of problem water with an assigned concentration of 50 µg/L selenium, or 144,000 to 163,000 acre-ft of subsurface drainage with an assigned concentration of 150 µg/L selenium). The flux of selenium from the drain to the Bay-Delta is projected to range from 117 to 182 lbs selenium per day. Tables B23b and B23c and figures B4a and B4b show a projected selenium rate (lbs selenium per day) from each of the five designated subareas of the western San Joaquin Valley using the minimum and maximum scenarios defined



Note: all ppb = µg/L selenium

Figure B2. Projected drainage volume and annual selenium loads for variable selenium concentrations (50, 150, 300 µg/L) for (*a*) Northern subarea, (*b*) Grassland subarea, (*c*) Westlands subarea, (*d*) Tulare subarea, and (*e*) Kern subarea.



Note: all ppb = µg/L selenium

Figure B3. Projected drainage volume and annual selenium loads for select minimum and maximum selenium concentrations (*a*) Northern subarea, (*b*) Grassland subarea, (*c*) Westlands subarea, (*d*) Tulare subarea, and (*e*) Kern subarea.

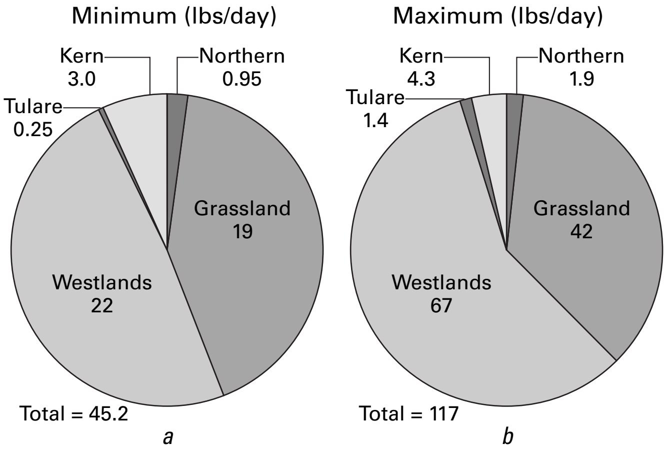


Figure B4. Projected (*a*) minimum and (*b*) maximum selenium flux (lbs per day) for the Northern, Grassland, Westlands, Tulare, and Kern subareas.

earlier from currently available data (figure B3). The projected range of selenium flux from each subarea is: Northern, 0.95 to 1.9 lbs per day; Grassland, 19 to 42 lbs per day; Westlands, 22 to 67 lbs per day; Tulare, 0.25 to 1.4 lbs per day; and Kern, 3.0 to 4.3 lbs per day. The projected total selenium flux is 45 to 117 lbs per day under the assumed conditions. Westlands and Grassland subareas are projected to account for the largest proportion of selenium load (figs. B4a and B4b). The projected range of combined loads from the Grassland and Westlands subareas is 0.86 to 2.29 ksts per year. For comparison, the current State limitation for the Grassland subarea to the San Joaquin River is 8,000 lbs per year or 0.46 ksts per year.

Appendix C. Agricultural Drainage Discharge to the San Joaquin River

Contents

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Tables

Models of Discharge to the San Joaquin River

In 1991 and 1992, the State acknowledged elevated levels of selenium in the San Joaquin River and parts of the Bay-Delta by designating specific segments or water bodies as *water-quality limited or impaired* (State Board, 2002). These include the lower 130-mile reach of the San Joaquin River, Suisun Bay, Carquinez Strait, San Pablo Bay, Central Bay, South Bay and the Delta. Discharge of selenium to the San Joaquin River has continued based on an agreement to implement a regulatory control program for selenium discharges, including recent adoption of selenium load limits and targets (State Board, 1985 and 1987; USBR, 1995 and 2001). Figure C1 shows the number of months per year that the USEPA's 5 µg/L selenium criterion was violated at the State compliance point for the San Joaquin River (San Joaquin River at Crows Landing) from 1986 to 1997. The number of violations is based on a monthly average of a varying number of collected grab samples (Central Valley Board, 1998d, e, f, g, h). Additionally in 1999, the State designated the San Joaquin River and parts of Bay-Delta as a high priority in the Consolidated Toxic Hot Spot Cleanup Plan (State Board, 1999c). Violations of the State annual selenium load limit (8,000 lbs selenium) have occurred at the San Joaquin River at Crows Landing from WY 1995 through 1998, when 14,291 lbs, 10,868 lbs, 8,667 lbs, and 13,445 lbs selenium, respectively, were discharged.

The Clean Water Act as amended in 1987 [section 303 (d)(l)(c)] requires that water-quality standards be converted into Total Maximum Daily Loads (TMDLs) in water-quality impaired water bodies like the lower reach of the San Joaquin River. A TMDL approach allows a State to implement water-quality control measures where beneficial uses are known to be impaired, but the resource is not being regulated because of lack of adequate data. In the case of selenium, both the existing record and developed models for the San Joaquin River have important limitations (Presser and Piper, 1998). From that record, it is difficult to ascertain if progress is being made, especially towards protecting the river (Westcot and others, 1996; Presser and Piper, 1998).

TMDL models used for the San Joaquin River are conservative-element dilution models that do not consider the potential for selenium to bioaccumulate in ecosystems (Environmental Defense Fund, 1994; Karkoski, 1996). The assimilative capacity of the river in existing models is defined only by flow (i.e., dilution capacity). In one derivation of a TMDL model, acknowledgement is made of the shortcomings of the approach by stating that, if in the future, load limits are derived based on the capacity of the ecosystem to safely absorb pollutants, the methodology to derive the load allowances would change, but implementation issues for the agricultural dischargers would remain the same (Environmental Defense Fund, 1994). Implementation issues may include a requirement for an economic justification of continued impairment of the beneficial uses of the river as prescribed by anti-degradation policies (Code of Federal Regulations 40:131.12; Clean Water Act Section 303(d) as amended, 1987). Hydrologic-economic models for the San Joaquin Valley and information regarding the cost/benefit of agriculture in the San Joaquin Valley have been developed and compiled at various stages of planning for irrigation and drainage projects (see, for example, Interagency Drainage Program, 1979a, b; Department of Water Resources, 1982; Horner, 1986; Willey, 1990; Dinar and Zilberman, 1991; Environmental Defense Fund, 1994; Central Board, 1996c). Monthly selenium concentrations greater than 5 µg/L have not occurred further downstream in the San Joaquin River at Vernalis, the entrance to the Bay-Delta.

Models that Target Load Reduction

Models were constructed in 1994 to calculate a load of selenium that might be discharged to the San Joaquin River with the goal of meeting a Federal 5 µg/L selenium criterion or a State 8 µg/L selenium objective. USEPA rejected the 8 µg/L objective for the San Joaquin River in 1992 and promulgated a 5 µg/L selenium criterion for the San Joaquin River and a 2 µg/L criterion for associated wetland channels (wildlife refuge supply channels) (USEPA, 1992). A TMDL model was developed by the Environmental Defense Fund and an alternative model named the Total Maximum Monthly Load (TMML) model was developed by the State (Central Valley Board, 1994b; Environmental Defense Fund, 1994). The Environmental Defense Fund model was a test case for agricultural non-point source pollution control that applied point source control regulation methodology. The model focuses on pollution sources, a program of load reductions, and economic incentives which include tradable discharge permits and tiered water pricing (Environmental Defense Fund, 1994). A modified version of a TMDL model for the San Joaquin River was adopted as part of a State *waste discharge permit* for the Grassland subarea in 1998 (Central Valley Board, 1998a).

The choice of a compliance site for load models and waste discharge permits has critical implications for the perception of water quality in the San Joaquin River. Little fresh water flows into the San Joaquin River upstream of Crows Landing due to regulation of the river by Friant Dam. Most of the San Joaquin River flow is diverted south through the Friant-Kern Canal, leaving agricultural drainage as the dominant source of flow in the river above its confluence with the Merced River. A compliance site upstream of the Merced River would be the most precautionary. It would closely reflect drainage quality and be indicative of conditions in the upstream 22 miles. A compliance site below confluence with the Merced River would be influenced by dilution water provided by the Merced River and leave the upstream segments unprotected. However, a downstream site is probably more indicative of water quality in the longer downstream segment.

The current compliance point for the San Joaquin River is designated as Crows Landing, downstream of the Merced River. The State permit for discharge to the San Joaquin River allows for a twelve-year compliance schedule. Full compliance for the San Joaquin River above and below the Merced River with a selenium water quality objective of 5 µg/L (4-day average) is scheduled for October 2010.

Variables considered in deriving selenium load allocations from TMDL-type models were:

- water-year type,
- water quality objective,
- averaging period,
- exceedance frequency, and
- flow derivation.

Table C1 and figures C2 to C4 give a summary of load allocations calculated from TMDL and TMML models using different types of water years. Figure C2 shows TMDL model loads for all water-year types (normal/wet, dry/below normal, and critically dry) for the case of a 5 µg/L objective, 4-day average, and a one-in-three-year violation rate. Figure C3 shows a comparison of TMDL and TMML model loads for a wet-year allocation under the same conditions as above. Figure C4 shows a comparison of TMDL and TMML model loads for a dry-year allocation under the same conditions as above. Tables C2 and C3 and figures C5 to C10 document in more detail load allocations for the San Joaquin River calculated for several different combinations of model assumptions using selenium water quality objectives of 8 or 5 µg/L. These data are compiled from documentation for TMDL and TMML models (Central Valley Board, 1994b and Environmental Defense Fund, 1994).

The base case for the San Joaquin River TMDL was a single design flow of about 92,000 acre-ft at 5 µg/L selenium. The model allocated a load of 1,248 lbs selenium (table C2) (Environmental Defense Fund, 1994). A quasi-static type TMDL model has three water-year classifications for the San Joaquin River (critically dry, dry/below normal, and above normal/wet; table C2 and figures C5 to C7). The TMML model, as submitted to USEPA for approval, derives loads for only two types of water years (critically dry/dry/below normal and above normal/wet; table C3 and figures C8 to C10).

Figures C5 to C10 also depict the seasonal nature of the models, with the greatest loads being discharged from December through May. Within a specific model, greater loads are allowed when dry-year water years are replaced by wet-year water years. Load allocations also increase when 4-day averages are replaced by monthly averages, and when allowable frequencies of violations of once-in-three-years are replaced by a frequency of once-in-five-months (figures C5 to C10). The TMDL model allows annual discharges to the San Joaquin River at Crows Landing/Patterson of 1,394 to 4,458 lbs selenium in dry years (critically dry, dry, and below normal years, table C1), within the ranges of options and excursion frequencies. The TMML model allows selenium discharges of 1,240 to 1,809 lbs per year in dry years. In wet years, the TMDL model allows selenium loads of 3,165 to 6,547 lbs per year and the TMML model allows loads of 3,760 to 5,334 lbs per year.

The Clean Water Act requires a *margin of safety* be considered in regulatory load models which are based solely on dilution. The purpose is to take into account uncertainties in the data or any lack of knowledge concerning the relation of effluent limitations and water quality (Environmental Defense Fund, 1994). Tables C1 to C3 show selenium loads used as 1) a margin of safety (a nominal 10 percent); and 2) estimated background loads from tributary rivers and wetlands. Margin of safety selenium loads range from 123 to 448 lbs per year in dry years and 317 to 534 lbs per year in wet years. Background selenium loads range from 91 to 273 lbs per year in dry years and 250 to 428 lbs per year in wet years. These loads were added to the modeled TMDL allowances for the dischargers, thereby increasing the modeled discharge to the San Joaquin River at Crows Landing (tables C1 to C3), but leaving in doubt protection of the San Joaquin River.

Models that Maximize Allowed Selenium Loads by Targeting Concentration

An alternative approach is to define a concentration target in a receiving water and manage selenium discharges to maintain that concentration under different flow conditions. Such a model, the dynamic real-time (DRT) model as suggested by the State, is designed to manage selenium loads using *dynamic* drainage effluent limits based on the *real-time* dilution capacity of the San Joaquin River (Karkoski, 1996; State Board, 1999a). The DRT approach depends on short-term forecasts of flow and concentrations. In this management approach, selenium load reduction is deferred to a plan of temporal storage and timed release of concentrated effluent to match dilution by tributary flows to obtain compliance with a 5 µg/L selenium objective. Timed-release of selenium-laden drainage takes maximum advantage of the dilution capacity of the river to maintain a given water quality objective (for example, the selenium concentration in the San Joaquin River will be maintained at 5 µg/L at all times). Note additionally for this approach that salinity measurements would need to act as surrogates for selenium measurements because technology is not available to assess selenium on a real-time basis.

Figure C11 shows an example, from limited data, of the DRT model loads for wet-year conditions using a 5 µg/L objective (Karkoski, 1996). Table C1 compares selenium loads allowed by a DRT model to those allocated by TMDL and TMML models, for a minimum, mean, and maximum amount of allowable loads of selenium discharged per month in a wet year. Figure C11 shows that an order-of-magnitude higher loads occurs in some months than that allowed by TMDL or TMML models (such as, 400 lbs selenium compared with 4,000 lbs). The selenium loads discharged for a wet year range from 2,605 to 17,605 lbs per year, with a mean of 7,347 lbs per year. A more recent reference to the DRT model shows the wet year load to be approximately that referenced in 1996 for a wet year (7,401 lbs per year) and a dry year value of 4,631 lbs per year (Drainage Implementation Program, 1999b).

With real-time drainage management, ponds for flow regulation would be necessary in order to maximize release of selenium loads during variable flow conditions in the river. The holding pond concept is reminiscent of planning for the San Luis Drain in the 1970s when Kesterson Reservoir ponds were to be used as holding reservoirs to regulate flows until the San Luis Drain was completed to the Bay-Delta. As mentioned earlier, more sophisticated storage, control, and timing are envisioned by managers and State regulators. Nevertheless, the ecological consequences of the ponds themselves need to be considered.

Managing a constant concentration in receiving waters, although in response to a TMDL requirement, is the goal of the dynamic-effluent-type of modeling. It is unclear whether this deviation from a load model target was the intended use of concentration-dependent water quality standards defined by USEPA. The DRT approach uses a receiving water body's dilution capacity to provide water to maximize disposal of selenium. Regulation of loads based on dynamic effluent limits provides no certainty for the amount discharged per month or year, nor for an assessment of the long-term progress toward selenium load reduction. The focus of TMDL and TMML models is to reduce or minimize selenium loads by establishing a load target. With real-time drainage management, the focus is shifted to a concentration target that, in essence, maximizes selenium loads by adjusting the timing of discharges to coincide with dilution capacity. As a result, the allowed selenium load would increase over that allocated by TMDL or TMML models. A DRT approach is best applied to maintaining a designated level of quality in the San Joaquin River as a receiving water. It is of less value in regulating the San Joaquin River as a source water for the Bay-Delta. In terms of ecosystem protection, this type of management could simulate a hydrologic system similar to a lake (lentic), rather than that of a flowing system (lotic), thus potentially expanding opportunities for selenium bioaccumulation.

Some additional practical considerations add complexity to applying a DRT concept. These include identifying a regulatory authority responsible for implementation of *real time* regulation. Uncertainty also exists about choice of a target concentration. Different agencies and stakeholders have called for revisions of the selenium objective upward from 5 µg/L to 8 µg /L, or downward to 2 µg/L. The choice of a compliance point (San Joaquin River at Patterson or Crows Landing or San Luis Drain at Mud Slough) will have a strong influence on the river, and therefore, is critical to determining an allowed load (as described above). Uncertainties about the type of conveyance used for drainage (wetland channels or the San Luis Drain) could have implications for concentrations. Since agricultural drainage is regulated as non-point source pollution, a 5 µg /L effluent stream from the discharger has not been required in the past. It is unclear how this would be integrated into a regulatory control program. Finally, refinement of the assimilative capacity operations plan using real-time management needs to include data collection to assess the assimilative capacity of the San Joaquin River based on the bioaccumulative nature of selenium (Grassland Area Farmers and San Luis and Delta-Mendota Water Authority, 1998; Presser and Piper, 1998). Understanding sources of selenium and how selenium moves through an agricultural discharge system becomes important in a strategy that maximizes loads to meet concentration objectives.

A second reason for modeling the influence of timed releases of agricultural discharges to the San Joaquin River is to help determine how to meet salinity objectives for the San Joaquin River at Vernalis (State Board, 1994, 1997, and 1999a; EA Engineering, Science, and Technology, 1999). The State model predicted that controlled timing of wetland releases (or a combination of drainage and wetland releases) did not achieve compliance with that standard. Focus then shifted toward taking advantage of additional seasonally available downstream dilution by releasing dilution water from the New Melones Reservoir on the Stanislaus River. Control of drainage release to the San Joaquin River also includes implementation of a system of storage including recycling facilities, evaporation ponds, and in-field subsurface storage (State Board, 1997). Despite several opportunities for manipulating the massively engineered Central Valley Project water supply, the ultimate alternative for salinity control seems to depend on managing the same lands that need drainage and that discharge selenium, but the State plan does not include an analysis of selenium effects.

Table C1. Modeled annual selenium load allocation and discharge from the Grassland Drainage Problem Area to the San Joaquin River using various models (Total Maximum Daily Load Model, Total Maximum Monthly Load Model, and Dynamic Real-Time Model), water-year types (critically dry; dry/below normal; above normal/wet, dry; or wet), averaging periods (4-day or monthly), and violation frequencies (1 in 3 year or 1 in 5 month) to achieve a 5 µg/L selenium objective for San Joaquin River.

Model and water year type	Irrigated/ drained acres	Range used to model selenium discharge (San Joaquin River at Crows Landing) (acre-ft/year)	Range of modeled selenium load allocations (lbs/year)	Range of modeled selenium background (lbs/year)	Range of modeled selenium margin of safety (lbs/year)	Range of modeled selenium discharge to San Joaquin R. at Crows Landing (lbs/year)
Total Maximum Daily Load Model, TMDL (5 µg/L selenium objective for San Joaquin River; 4-day or monthly averaging period; 1 in 3 year or 1 in 5 month violation rate)						
TMDL[a]	93,390/49,273	–	–	–	–	–
Critically dry [b]	–	104,030–260,859	1,163–3,060	91–129	140–352	1,394–3,541
Dry/Below normal[b]	–	225,995–328,002	2,504–3,737	257–273	305–448	3,066–4,458
Above normal/wet[b]	–	233,186–481,934	2,598–5,463	250–428	317–656	3,165–6,547
Total Maximum Monthly Load Model, TMML (5 µg/L selenium objective for San Joaquin River; 4-day or monthly averaging period; 1 in 3 year violation frequency)						
TMML[c]	90,620/44,860	–	–	–	–	–
Dry[b]	–	91,255–133,210	1,001–1,514	114–116	123–179	1,240–1,809
Wet[b]	–	276,772–392,570	3,088–4,451	294–362	381–534	3,760–5,334
Dynamic Real-Time Model, DRT (5 µg/L selenium objective for San Joaquin River)						
DRT [d] wet [b]	–	–	2,605–17,605 (7,347 mean)	–	–	–

[a] Environmental Defense Fund, 1994; Central Valley Board, 1994b.

[b] Critically dry (< 2.1 million acre-ft); dry (2.1-2.5 million acre-ft); (below normal 2.5-3.1 million acre-ft); above normal (3.1-3.8 million acre-ft); and wet (>3.8 million acre-ft) (Central Valley Board, 1994b, Table 7); referenced to San Joaquin River Index threshold (Central Valley Board, 1994b).

[c] Draft submittal to USEPA from Central Valley Board, 1996a.

[d] Calculated effluent limits for wet year based on 22 year period of record (Karkoski, 1996).

Table C2. Modeled annual selenium load allowance from the Grassland Area to the San Joaquin River and modeled flow for the San Joaquin River at Crows Landing/ Patterson using the Total Maximum Monthly Load Model under various water-year types (critically dry; dry/below normal; or above normal/ wet), averaging periods (4-day or monthly), and violation frequencies (1 in 3 year or 1 in 5 month) to achieve a 5 µg/L selenium objective for San Joaquin River.

[The Total Maximum Daily Load Model was developed by the Environmental Defense Fund (1994) and the Central Valley Board (1994b). Modeled effluent load data from October, 1985 to December, 1988. Modeled San Joaquin River flow at Crows Landing and Patterson from WY 1970 to 1991. Note: flow record for Crows Landing is from 1970-1972; the remainder of the data used in the model for the San Joaquin River at Crows Landing was reconstructed from flow data collected at San Joaquin River at Patterson. Data also was *adjusted* for averaging period because record is incomplete (Central Valley Board, 1994b; Karkoski, 1996).]

Selenium performance goal or regulation scenario	Irrigated/drained acreage[a] (acres)	Modeled selenium load allocation (lbs/year)	Modeled selenium background (lbs/year)	Modeled selenium margin of safety (lbs/year)	Modeled selenium discharge to San Joaquin River at Crows Landing/ Patterson (lbs/year)	Modeled flow of San Joaquin River at Crows Landing/ Patterson) (acre-ft/year
Total Maximum Daily Load Model, TMDL (single design flow; 5 µg/L selenium objective for San Joaquin River; 4-day average; 1 in 3 year violation frequency)						
TMDL	93,390/49,273	1,248	–	–	–	92,363
Total Maximum Daily Load Model, TMDL (5 µg/L selenium objective for San Joaquin River; 4-day average; 1 in 3 year violation frequency)						
TMDL	93,390/49,273	–	–	–	–	–
Critically dry[b]	–	1,163	110	140	1,415	104,030
Dry/below normal[b]	–	2,504	257	305	3,069	225,995
Above normal/wet[b]	–	2,598	250	317	3,166	233,186
Total Maximum Daily Load Model, TMDL (5 µg/L selenium objective for San Joaquin River; monthly average; 1 in 3 year violation frequency)						
TMDL	93,390/49,273	–	–	–	–	–
Critically dry[b]	–	1,676	119	200	1,994	147,029
Dry/Below normal[b]	–	3,036	265	366	3,666	270,000
Above normal/wet[b]	–	3,374	280	405	4,061	299,049
Total Maximum Daily Load Model, TMDL (5 µg/L selenium objective for San Joaquin River; 4-day average; 1 in 5 month violation frequency)						
TMDL	93,390/49,273	–	–	–	–	–
Critically dry[b]	–	3,060	129	352	3,546	260,859
Dry/Below normal[b]	–	3,737	273	448	4,454	328,002
Above normal/wet[b]	–	5,463	428	656	6,549	481,934

[a] Table II-4, Baseline Data for Pollution Allocation Subtotal (Environmental Defense Fund, 1994). Acreage does not include 10,000 irrigated acres and 5,276 drained acres as noted in total acreage taken from water district data for various years (1987-1990) and Central Valley Board data.

[b] Critically dry (< 2.1 million acre-ft); dry (2.1-2.5 million acre-ft); (below normal 2.5-3.1 million acre-ft); above normal (3.1-3.8 million acre-ft); and wet (>3.8 million acre-ft) (Central Valley Board, 1994b, Table 7); referenced to San Joaquin River Index threshold (Central Valley Board, 1994b).

Table C3. Modeled annual selenium load allowances from the Grassland Area to the San Joaquin River and modeled flow for the San Joaquin River at Crows Landing/Patterson using various models (Total Maximum Monthly Load or Dynamic Real-Time), water-year types (critically dry/dry/below normal; above normal/wet; or wet), averaging periods (4-day or monthly), and violation frequencies (1 in 3 year) to achieve either a 8 or 5 µg/L selenium objective for San Joaquin River.

[Modeled effluent load data from October, 1985 to December, 1988. Modeled San Joaquin River flow at Crows Landing and Patterson from WY 1970 to 1991. Note: flow record for Crows Landing is from 1970-1972; the remainder of the data used in the model for the San Joaquin River at Crows Landing was reconstructed from flow data collected at San Joaquin River at Patterson. Data also was *adjusted* for averaging period because record is incomplete (Central Valley Board, 1994b; Karkoski, 1996).]

Selenium performance goal or regulation scenario	Irrigated/drained acreage[a] (acres)	Modeled selenium load allocation (lbs/year)	Modeled selenium background (lbs/year)	Modeled selenium margin of safety (lbs/year)	Modeled selenium discharge to San Joaquin R. at Crows Landing/ Patterson (lbs/year)	Modeled flow San Joaquin River at Crows Landing/ Patterson (acre-ft/year)
Total Maximum Monthly Load Model, TMML (8 µg/L selenium objective for San Joaquin River; monthly mean; 1 in 3 year violation frequency)						
TMML[b]	90,620/44,860	–	–	–	–	–
Critically dry/dry/below normal	–	2,491	114	290	2,896	133,210
Total Maximum Monthly Load Model, TMML (5 µg/L selenium objective for San Joaquin River; 4-day average; 1 in 3 year violation frequency)						
TMML[b]	90,620/44,860					
Critically dry/dry/below normal	–	1,001	116	123	1,240	91,255
Above normal/wet	–	3,088	294	381	3,760	276,772
Total Maximum Monthly Load Model, TMML (5 µg/L selenium objective for San Joaquin River; monthly average; 1 in 3 year violation frequency)						
TMML[b]	90,620/44,860	–	–	–	–	–
Critically dry/dry/below normal	–	1,514	114	179	1,809	133,210
Above normal/wet	–	4,451	362	534	5,334	392,570
Dynamic Real-Time Model, DRT						
DRT[c]	–	–	–	–	–	–
Wet (mean)	–	7,347	–	–	–	–
Wet (minimum)	–	2,605	–	–	–	–
Wet (maximum)	–	17,605	–	–	–	–

[a] Table 1 (Central Valley Board, 1994b).

[b] Draft submittal of TMML Model to USEPA (Central Valley Board, 1996a).

[c] Karkoski, 1996.

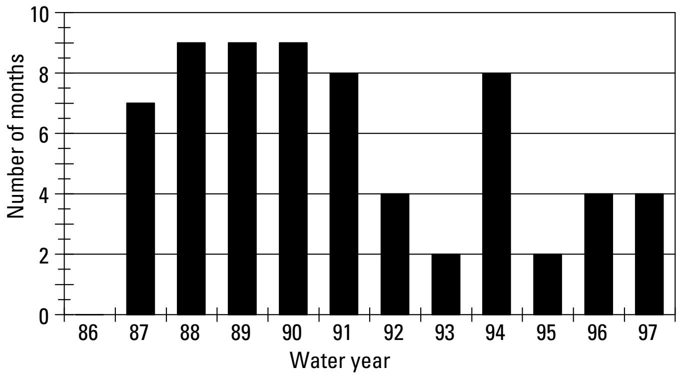

Figure C1. Number of selenium water quality exceedance months (U.S. EPA criterion) for the San Joaquin River at Crows Landing during WY 1986 through WY 1997.

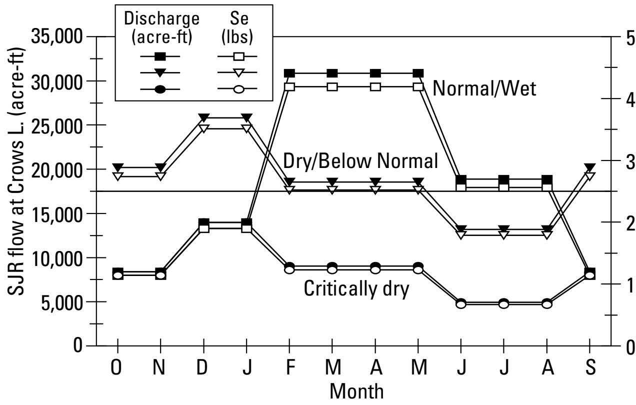

Figure C2. Comparison of wet, dry, and critically dry years (TMDL model) for 5 µg/L, 4-day average, 1 out of 3 year exceedance.

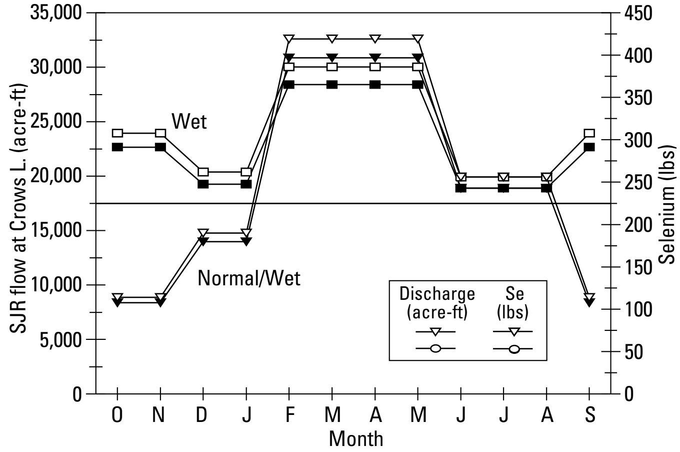

Figure C3. Comparison of TMDL and TMML model projections during a wet year for 5 µg/L, 4-day average, 1 out of 3 year exceedance.

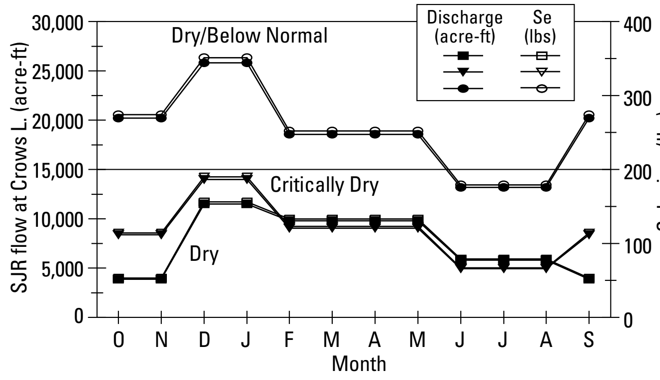

Figure C4. Comparison of TMDL and TMML model projections during a dry year for 5 µg/L, 4-day average, 1 out of 3 year exceedance.

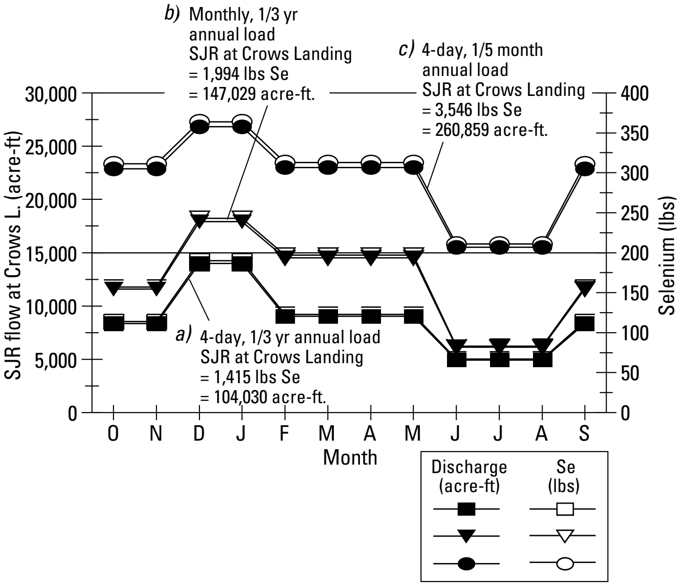

Figure C5. Comparison of TMDL model projections at Crows Landing during critically dry years for (*a*) 5 µg/L, 4-day average, 1 out of 3 year exceedance, (*b*) 5 µg/L, monthly average, 1 out of 3 year exceedance, and (*c*) 5 µg/L, 4-day average, 1 out of 5 month exceedance.

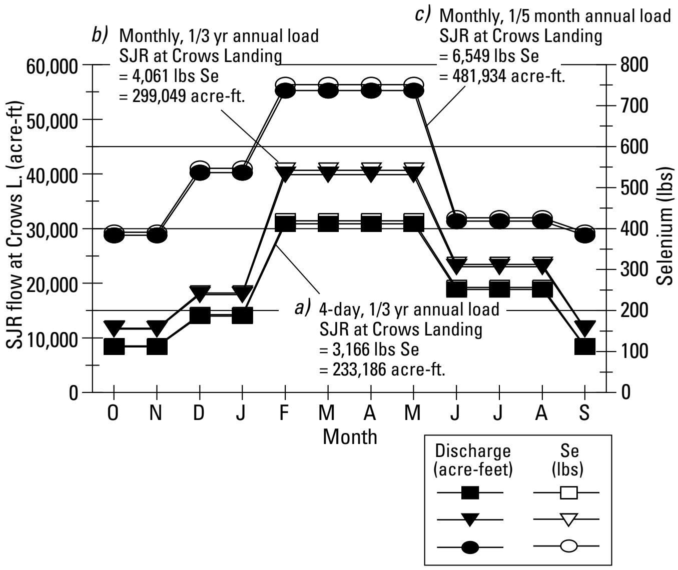

Figure C7. Comparison of TMDL model projections at Crows Landing during above normal and wet years for (*a*) 5 µg/L, 4-day average, 1 out of 3 year exceedance, (*b*) 5 µg/L, monthly average, 1 out of 3 year exceedance, and (*c*) 5 µg/L, 4-day average, 1 out of 5 month exceedance.

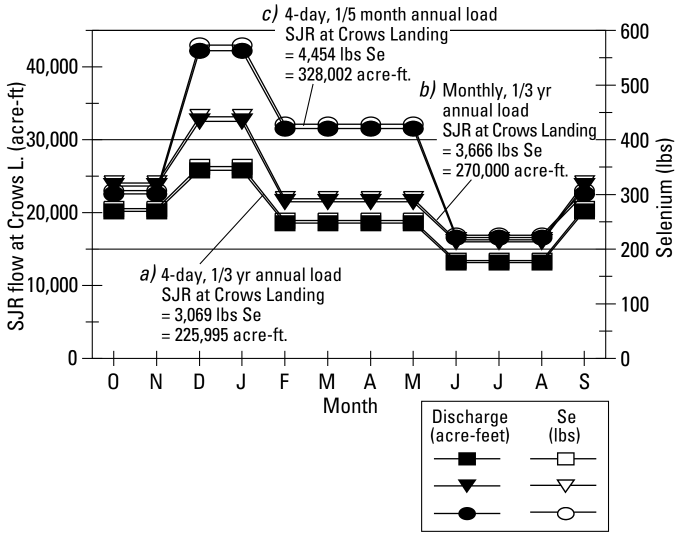

Figure C6. Comparison of TMDL model projections at Crows Landing during dry and below normal years for (*a*) 5 µg/L, 4-day average, 1 out of 3 year exceedance, (*b*) 5 µg/L, monthly average, 1 out of 3 year exceedance, and (*c*) 5 µg/L, 4-day average, 1 out of 5 month exceedance.

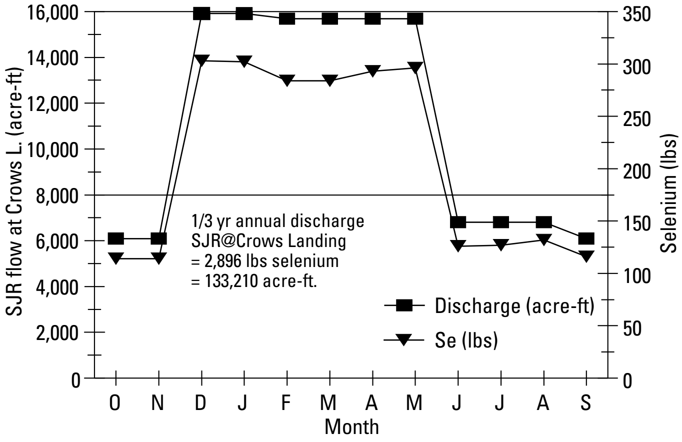

Figure C8. TMML model projection at Crows Landing for 8 µg/L and 1 out of 3 year exceedance.

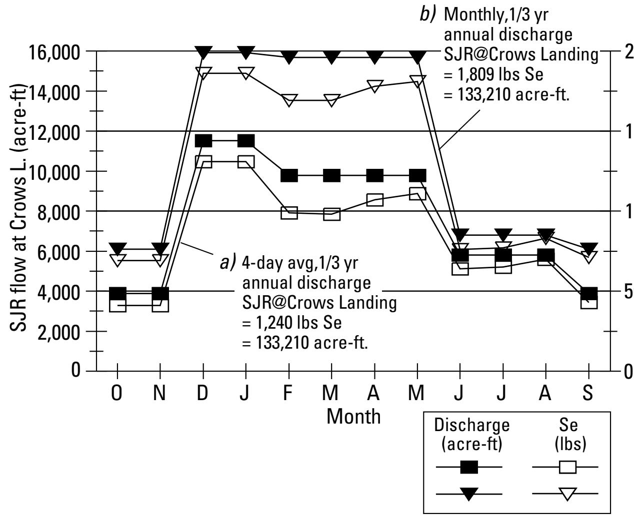

Figure C9. Comparison of TMML model projections during a dry year at Crows Landing for (*a*) 5 µg/L, 4-day average inputs, 1 out of 3 years exceedance, and (*b*) 5 µg/L and monthly average, 1 out of 3 years exceedance.

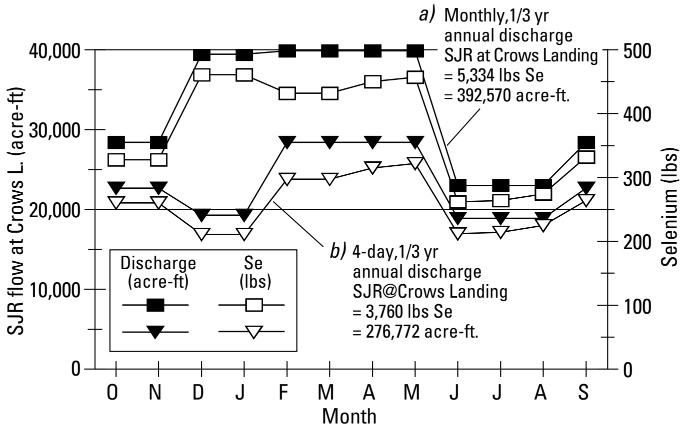

Figure C10. Comparison of TMML model projections during a wet year at Crows Landing for (*a*) 5 µg/L, monthly average, 1 out of 3 years exceedance, and (*b*) 5 µg/L, 4-day average, 1 out of 3 year exceedance.

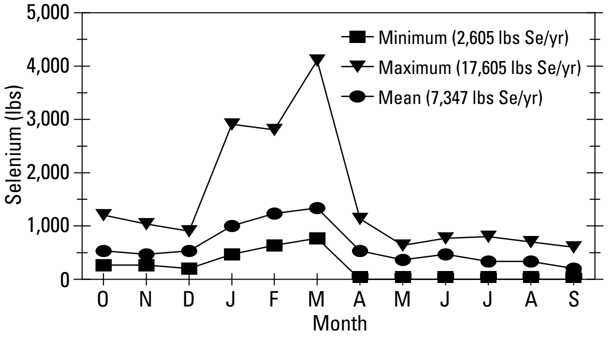

Figure C11. Monthly selenium loads for a dynamic real time (DRT) model during a wet year using a 5 µg/L input.

Appendix D. Temporal and Spatial Variability in Selenium Load

Contents

Figures

Tables

Introduction

Estimates of selenium loads in this report contain some substantial uncertainties that have not yet been discussed. The most important of these are associated with the temporal and spatial dependence of selenium loads or the ways those loads are determined. Given here are a series of graphs based on available data that document the variability in the quality of agricultural drainage that is discharged to the San Joaquin River and a 28-mile portion of the San Luis Drain re-opened as part of the Grassland Bypass Channel Project. Flow and concentration data also are compiled and graphed as determinants of load. Compilations such as these could be useful in helping to design monitoring plans to collect data suitable for more detailed projections, which are essential in the future.

Data from the Grassland Drainage Problem Area (DPA) and the San Luis Drain outflow to Mud Slough (site B) characterize drainage from a source area (farmland sumps or agricultural drainage canals). Sites downstream from the source area and the San Luis Drain outflow are Mud Slough (MS); Salt Slough (SS); the San Joaquin River at Crows Landing/Patterson below the confluence with the Merced River (CL/PATT, about 50 miles downstream from farm sumps); and the San Joaquin River at Vernalis (VERN, about 130 miles downstream from agricultural discharges).

Data sets mainly encompass WY 1986 to WY 1998. Focus here is on WYs 1997 and 1998 data sets because these were the first years in which data were collected at greater frequency than had been the case historically.

Temporal Variability

Seasonal and inter-annual variability

Salt imbalance in the San Joaquin Valley is also a driving force for management activities. Selenium loads are compared to salt loads to elucidate the behavior of a non-conservative element (selenium) to that of a conservative element (salt). Total dissolved solids concentrations or specific conductance is used here as a surrogate for salt concentrations. Salt concentrations are calculated from specific conductance by using the equation:

Specific conductance × 0.65 = mg/L total dissolved solids (TDS) or salt

Salt or TDS load (in tons) is calculated using the equation:

[salt or TDS concentration (mg/L) × drainage volume (acre-ft)] × 0.00136 = salt or TDS load (tons),

where 0.00136 tons salt or TDS per acre-foot is equal to a concentration of 1 mg/L salt or TDS. Pounds can be converted to tons using the conversion factor: tons = lbs ÷ 2,000. Conversion factors used for salt and selenium were compiled previously (see main text table 4).

Monthly, Daily and Hourly Measurements

Monitoring for the Grassland Bypass Channel Project provides for frequent measurements of flow and concentrations in the re-opened 28-mile portion of the San Luis Drain (USBR and others, 1996). Salt and selenium loads for the Grassland Drainage Problem Area were measured at the San Luis Drain outflow to Mud Slough (site B) for WYs 1997 and 1998 (also see appendix B, tables B8 and B9) (USBR and others, 1998 and ongoing). Figures D1 and D2 show the variation for WYs 1997 and 1998 in monthly San Luis Drain flow (averages of daily flow measurements), monthly selenium concentrations (averages of daily measurements), monthly salt concentrations [averages of daily specific conductance converted to total dissolved solids or salt concentration], and calculated monthly selenium and salt loads. For the Grassland Bypass Channel Project, drainage management is aimed at meeting monthly selenium load targets that are based on the seasonal nature of drainage generation (listed in appendix B, tables A8 and A9 and shown in appendix A, figure A11). Maximum pre-irrigation occurs in February, maximum irrigation in July, and maximum discharge in February or March. Ranges of monthly variation for WY 1997 are: flow, 1,274 to 4,867 acre-ft; selenium concentration 25 to 105 µg/L; salt concentration 2,175 to 3,255 mg/L; selenium load 109 to 1,278 lbs; and salt load 4,325 to 20,091 tons. Ranges of monthly variation for WY 1998 are: flow, 1,403 to 7,094 acre-ft; selenium concentration 43 to 105 µg/L; salt concentration 2,391 to 3,704 mg/L; selenium load 178 to 1,598 lbs; and salt load 5,563 to 31,182 tons.

Figures D3 and D4 show the daily variation for WYs 1997 and 1998 in San Luis Drain flow (continuous monitoring based on 20-minute interval measurements), selenium concentrations, TDS or salt concentrations (based on specific conductance measurements), selenium loads, and salt loads (USBR and others, 1998 and ongoing). Ranges of daily variation for WY 1997 are: flow 21 to 181 acre-ft; selenium concentration 15 to 116 µg/L; and salt concentration 1,703 to 3,671 mg/L. Daily loads vary from 1.1 to 54 lbs selenium and 66 to 860 tons salt. Ranges of daily variation for WY 1998 are: flow 20 to 288 acre-ft; selenium concentration 20 to 128 µg/L; and salt concentration 4,114 to 2,230 mg/L. Daily loads vary from 2.7 to 69 lbs selenium and 83 to 1,218 tons salt.

Figure D5 shows the hourly variation in selenium concentration and conductivity for the San Luis Drain discharge during a 24-hour interval (Rudy Schnagl, Central Valley Board, personal commun., June, 1998). Ranges of hourly variations are: selenium concentration 47 to 78 µg/L; and conductivity 4,280 to 4,675 µmhos/cm (equivalent to 2,782 to 3,039 mg/L total dissolved solids).

Figure D6 compares monthly selenium load and concentration data for the San Joaquin River at Crows Landing

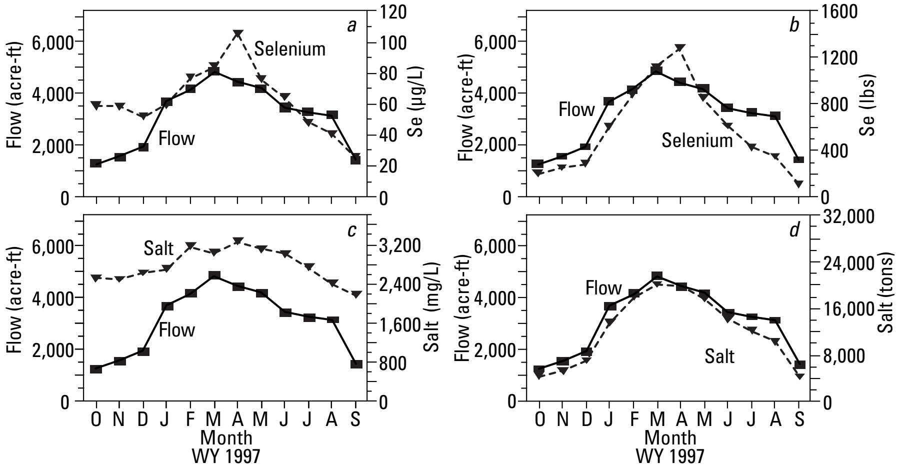

Figure D1. Relation between flow and (*a*) selenium concentration; (*b*) selenium load; (*c*) salt concentration; and (*d*) salt load on a monthly basis for site B (San Luis Drain outflow to Mud Slough) during WY 1997.

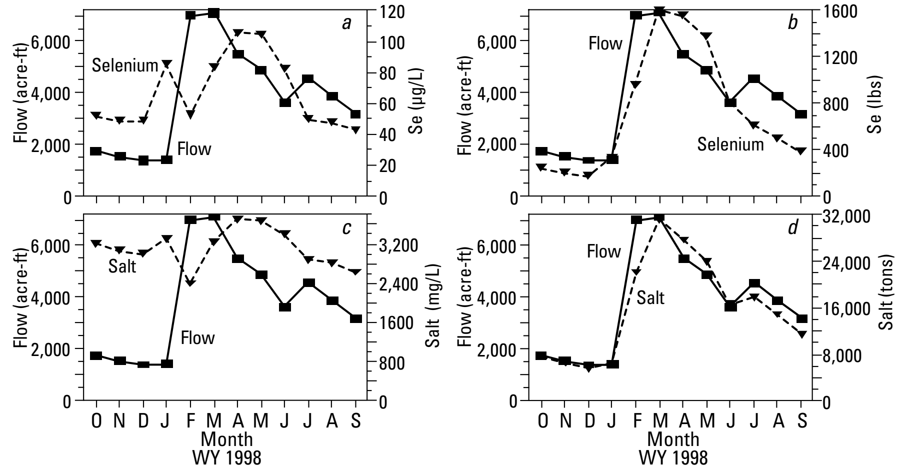

Figure D2. Relation between flow and (*a*) selenium concentration; (*b*) selenium load; (*c*) salt concentration; and (*d*) salt load on a monthly basis for site B (San Luis Drain outflow to Mud Slough) during WY 1998.

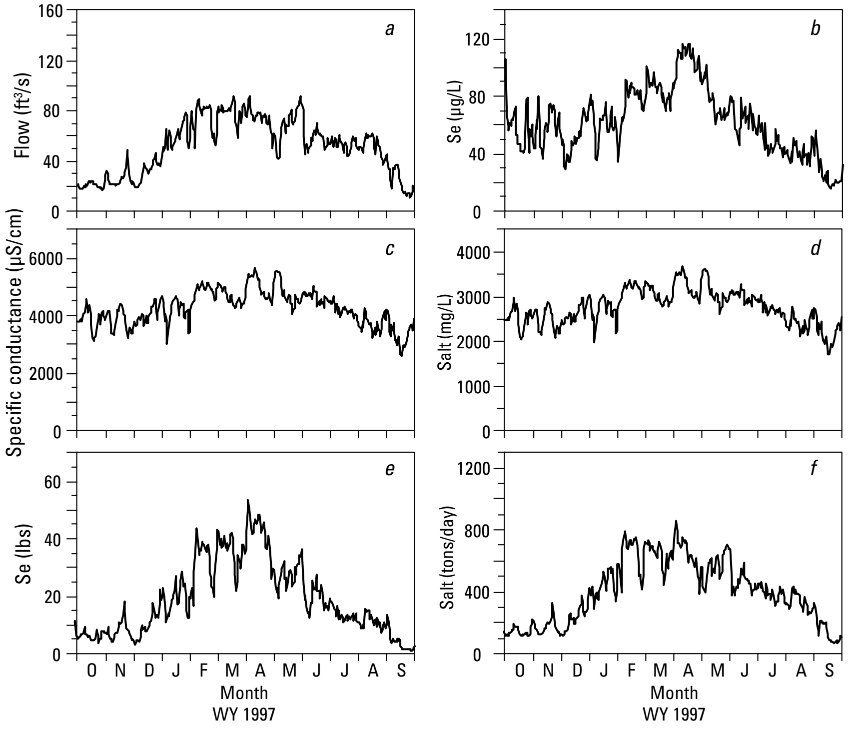

Figure D3. Daily variation of (*a*) flow; (*b*) selenium concentration; (*c*) specific conductance; (*d*) total dissolved solids; (*e*) selenium load; and (*f*) salt load for site B (San Luis Drain outflow to Mud Slough) during WY 1997.

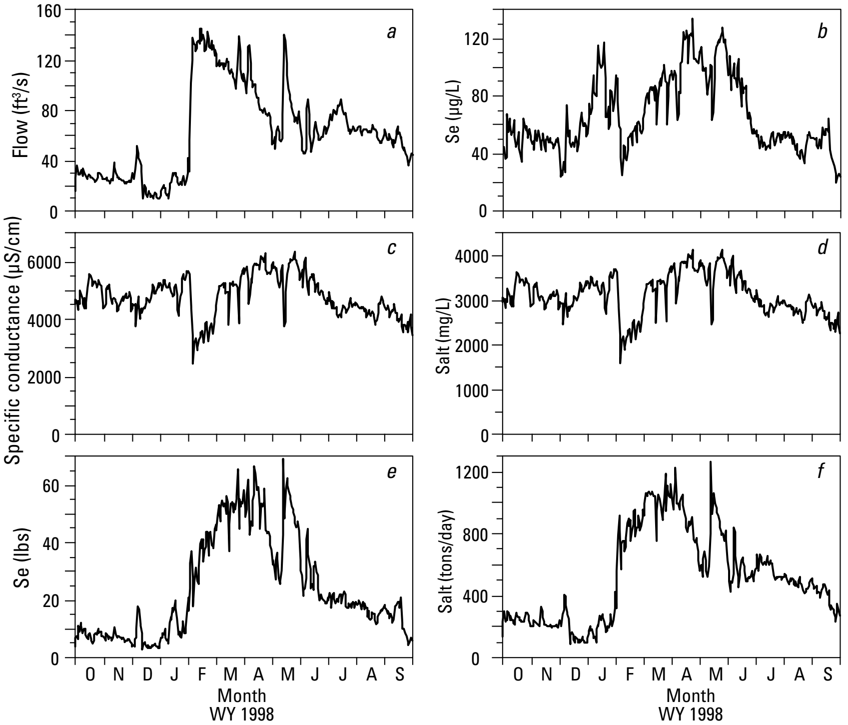

Figure D4. Daily variation of (*a*) flow; (*b*) selenium concentration; (*c*) specific conductance; (*d*) total dissolved solids; (*e*) selenium load; and (*f*) salt load for site B (San Luis Drain outflow to Mud Slough) during WY 1998.

downstream of the San Luis Drain discharge for WYs 1997 and 1998 (USBR and others, 1998 and ongoing). In WY 1997, selenium concentrations were lower compared to those of WY 1998. Flow in the San Joaquin River below the Merced River was sustained at a higher level for a longer period in WY 1998 than in WY 1997 due to increased snowmelt flowing in the Merced River. The competing seasonal effects of increased source load due to increased applied water and dilution afforded by the Merced River resulted in a selenium load of 9,054 lbs for WY 1997; and 15,884 lbs for WY 1998. Violation of the 5 µg/L selenium criterion occurred at this site in WY 1997, but not in WY 1998. Figure D7 compares salt load and concentration data for the San Joaquin River at Crows Landing for WYs 1997 and 1998. Salt load and concentration patterns generally follow those for selenium load and concentration in WY 1997, but the salt concentration pattern deviates from that of selenium concentration in WY 1998. Ranges of monthly variation for WY 1997 are: flow 28,761 to 1,212,948 acre-ft; selenium concentration, 0.36 to 6.8 µg/L; salt concentration 109 to 952 mg/L; selenium load, 149 to 1,533 lbs; and salt load, 24,563 to 242,735 tons. Ranges of monthly variation for WY 1998 are: flow

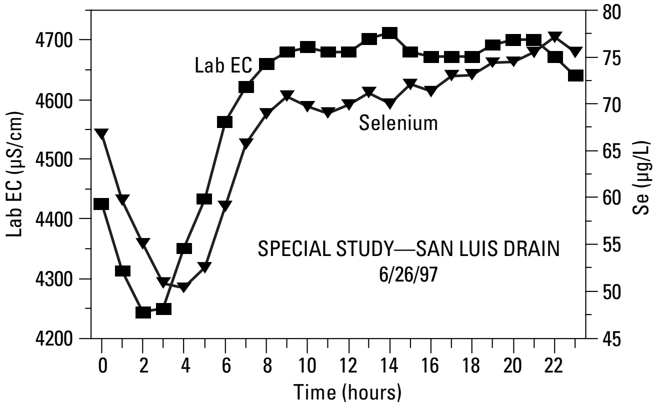

Figure D5. Relations between electrical conductance and selenium concentrations on an hourly basis for site B (San Luis Drain outflow to Mud Slough).

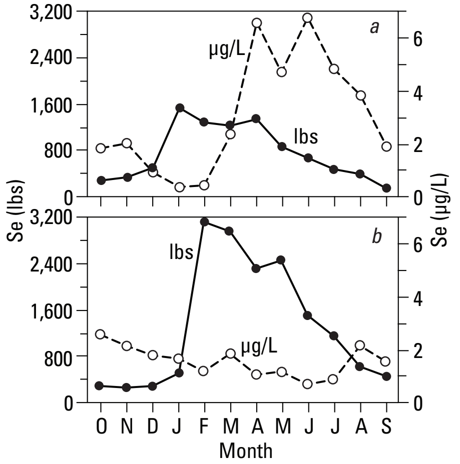

Figure D6. Relation between selenium concentration and load for the San Joaquin River at Crows Landing during (*a*) WY 1997 and (*b*) WY 1998.

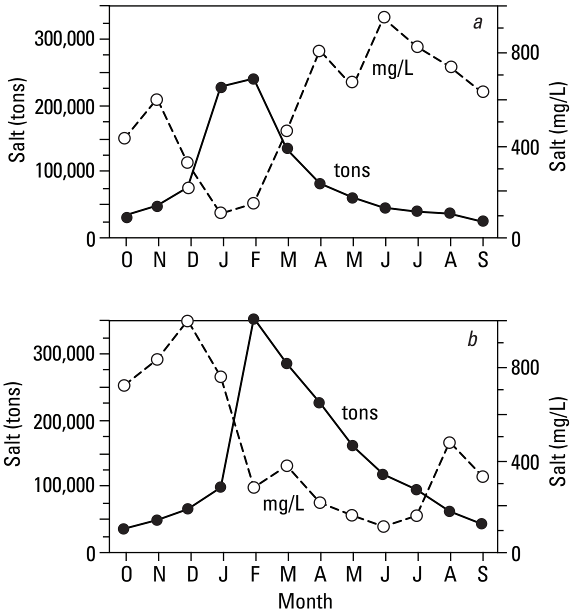

Figure D7. Relation between salt concentration and load for the San Joaquin River at Crows Landing during (*a*) WY 1997 and (*b*) WY 1998.

40,200 to 998,158 acre-ft; selenium concentration, 0.69 to 2.6 µg/L; salt concentration 108 to 934 mg/L; selenium load, 262 to 3,133 lbs; and salt load, 37,006 to 284,356 tons.

Daily measurements of salt and selenium also were taken during WYs 1997 and 1998 for the San Joaquin River at Crows Landing (USBR and others, 1998 and ongoing). Figure D8 shows the WY 1997 daily variation of flow, concentration, and load. Ranges of daily variation for WY 1997 are: flow 818 to 73,458 acre-feet; selenium concentration 0.1 to 9.7 µg/L; salt concentration 82 to 1,165 mg/L; selenium load 1.3 to 183 lbs; and salt load 500 to 15,956 tons. Figure D9 shows the WY 1998 daily variation of flow, selenium and salt concentrations, and calculated daily selenium and salt loads. Ranges of daily variation for WY 1998 are: flow 483 to 24,200 cfs or 956 to 47,916 acre-feet; selenium concentration 0.5 to 4.1 µg/L; salt concentration 79 to 1,165 mg/L; selenium load 3.4 to 183 lbs; and salt load 809 to 15,482 tons.

Spatial Variability

Tables D1 and D2 show the percentage of input selenium (non-conservative element) and salt (conservative element) loads to the discharged load of selenium and salt for the San Joaquin River at Vernalis, which is the entrance to the Bay-Delta (Central Valley Board, 1996a, b, 1998d, e, f, g, h). These

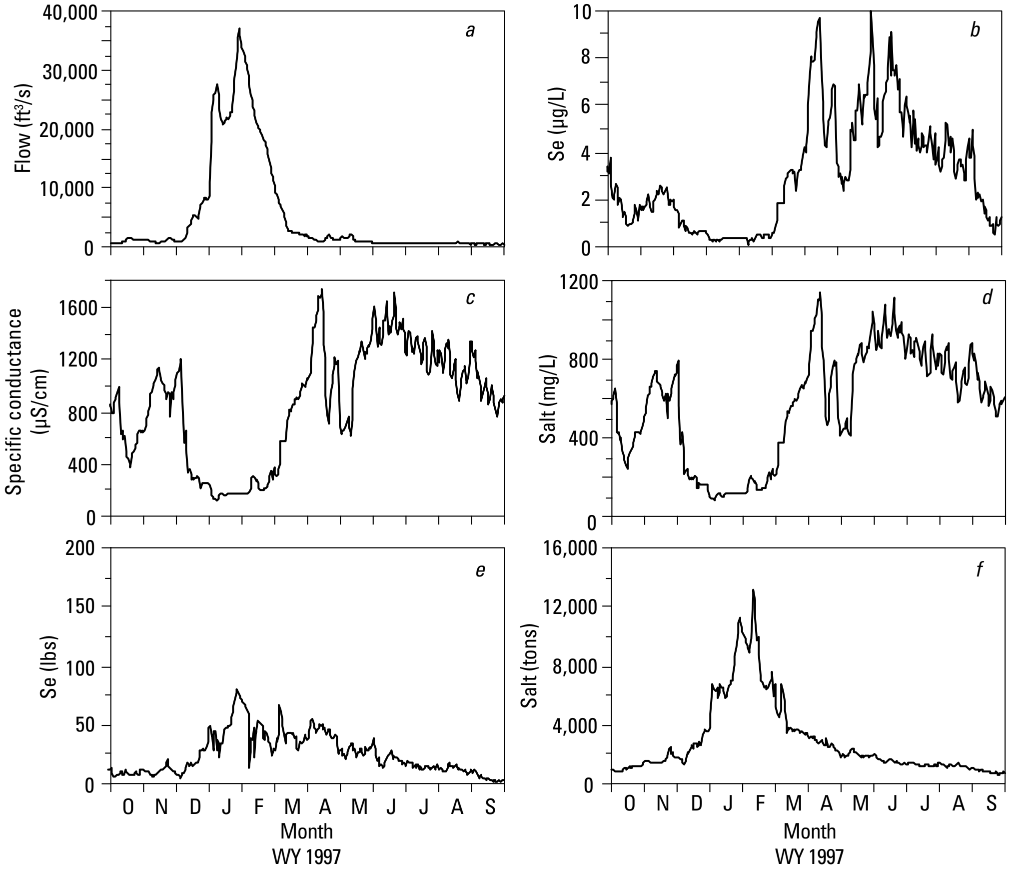

Figure D8. Daily variation of (*a*) flow; (*b*) selenium concentration; (*c*) specific conductance; (*d*) total dissolved solids; (*e*) selenium load; and (*f*) salt load for the San Joaquin River at Crows Landing during WY 1997.

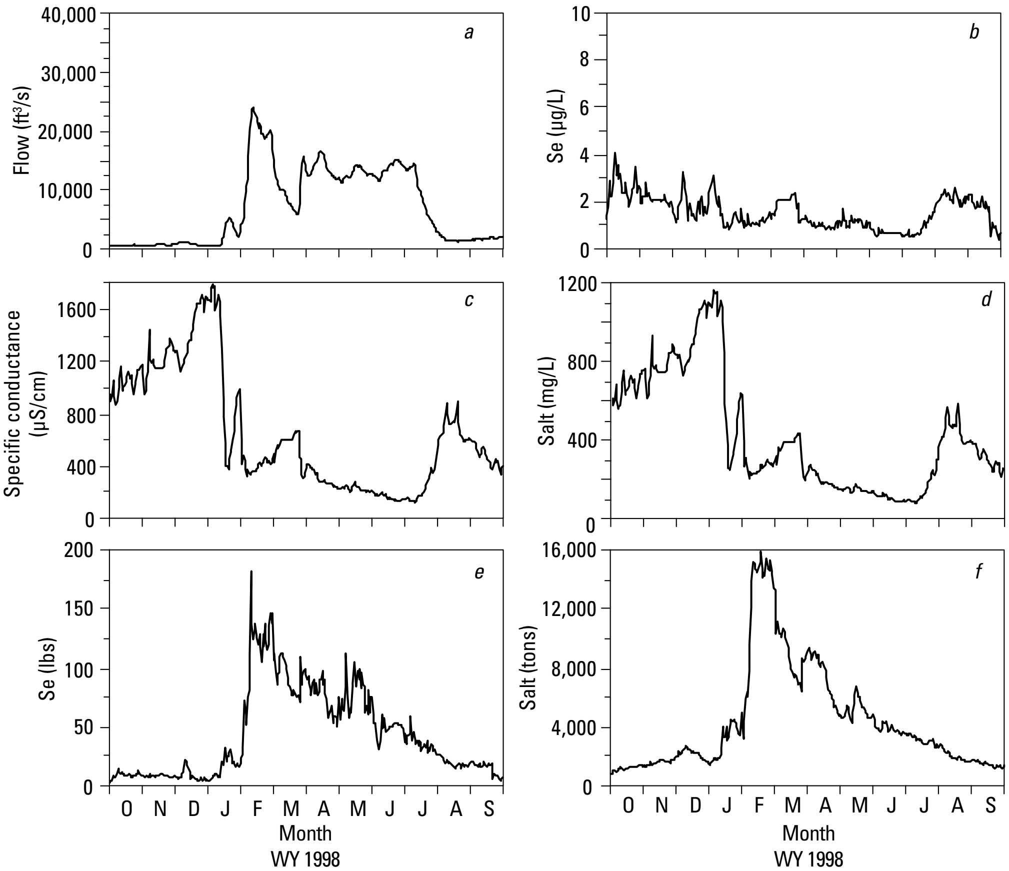

Figure D9. Daily variation of (*a*) flow; (*b*) selenium concentration; (*c*) specific conductance; (*d*) total dissolved solids; (*e*) selenium load; and (*f*) salt load for the San Joaquin River at Crows Landing during WY 1998.

data for WYs 1986 to 1997 show that 62 to 162 percent of the San Joaquin River selenium load is discharged above or at the Merced River inflow to the river, which would include loads from both slough and river sources (the San Joaquin River is the only outlet from the San Joaquin Valley). The Merced River inflow to the San Joaquin River is about 60 miles above Vernalis. Between the Merced River confluence and Vernalis, the Tuolumne and Stanislaus Rivers flow into the San Joaquin River. About 68 to 87 percent of the San Joaquin River salt load is discharged above or at the Merced River inflow to the river. Figure D10 shows the percent of the selenium load from the Drainage Problem Area, combined Mud and Salt Sloughs, and Crows Landing/Patterson normalized to the selenium load at the San Joaquin River at Vernalis. Figure D11 shows the percent of the salt load from the Drainage Problem Area, combined Mud and Salt Sloughs, and Crows Landing/Patterson normalized to the salt load at the San Joaquin River at Vernalis. The pattern of behavior of non-conservative selenium is different from that of conservative salt. The selenium loads measured as the input to the system (primary drainage canals, Drainage Problem Area) are perpetually different from those measured as the outputs from the system (downstream in wetland sloughs or the San Joaquin River). Downstream selenium loads show both decreases (measured at Salt and Mud Sloughs) and increases (San Joaquin River at Crows Landing and Vernalis) (also see appendix B, tables B4 to B7).

Table D1. Selenium loads from the Grassland Drainage Problem Area, Mud and Salt Sloughs, and the San Joaquin River at Crows Landing-Patterson as a percentage of selenium loads at the San Joaquin River at Vernalis.

Selenium (lbs/year)	Grassland Drainage Problem Area/San Joaquin R. at Vernalis (%)	Mud and Salt Sloughs/San Joaquin R. at Vernalis (%)	San Joaquin R. at Crows Landing-Patterson/San Joaquin R. at Vernalis (%)
1986	65	46	72
1987	126	88	101
1988	120	96	110
1989	100	93	85
1990	99	103	82
1991	162	108	98
1992	143	82	86
1993	99	77	92
1994	109	102	94
1995	69	62	83
1996	88	83	94
1997	62	69	77

Table D2. Salt loads (Total Dissolved Solids) from the Grassland Drainage Problem Area, Mud and Salt Sloughs, and the San Joaquin River at Crows Landing-Patterson as a percentage of salt loads at the San Joaquin River at Vernalis.

Salt (tons/ year)	Grassland Drainage Problem Area/San Joaquin R. at Vernalis (%)	Mud and Salt Sloughs/San Joaquin R. at Vernalis (%)	San Joaquin R. at Crows Landing-Patterson/ San Joaquin R. at Vernalis (%)
1986	17	17	78
1987	27	27	79
1988	28	28	86
1989	28	28	75
1990	25	25	79
1991	27	27	87
1992	24	24	85
1993	21	21	78
1994	24	24	84
1995	17	17	87
1996	17	17	68
1997	10	10	74

In the absence of the San Luis Drain extension to the Bay-Delta, which would provide a single source of selenium at a single discharge point, loads discharged from the San Joaquin River at Vernalis are not likely to equal loads discharged into the river from the drainage source area.

As noted in appendix B, selenium is persistently discharged from the Grassland area to the San Joaquin River, but selenium loads are dependent on monitoring site location within the Grassland area (also see main text table 5; appendix B, tables B4 to B7; appendix A, figures A9 and A10). The upstream discharge represents managed components of flow and load. Data for WYs 1986 to 1998 generally can be related to physical variables that affect drainage conditions (for example, drought in 1987 through 1992; California Coast Range flooding in 1995; and Sierra Nevada flooding in winter 1997–1998; also see appendix A, fig. A10). Ranges of yearly variation for WYs 1986 to 1997 for the Drainage Problem Area are: flow, 24,533 to 67,006 acre-ft; selenium concentration 52 to 80 µg/L; selenium load 5,083 to 10,959 lbs. Ranges of yearly variation are for Mud and Salt Sloughs are: flow, 85,428 to 288,253 acre-ft; selenium concentration 10 to 16 µg/L; selenium load 2,919 to 10,694 lbs. Combining the data for Mud and Salt sloughs dampens the variation seen in each slough when influenced by agricultural discharge. Ranges of yearly variation for the San Joaquin River at Crows Landing/ Patterson are: flow, 0.29 to 4.18 million acre-ft per year; selenium concentration 1 to 6.3 µg/L; and selenium load 3,064 to 14,291 lbs per year. Ranges of yearly variation for the San Joaquin River at Vernalis are: flow, 0.66 to 6.77 million acre-ft per year; selenium concentration 0.6 to 3.0 µg/L; and selenium load 3,611 to 17,238 lbs per year.

Except for WY 1990, selenium input loads (upstream drainage canals, Drainage Problem Area, appendix B, table B4) from 1986 to 1995 are higher than output loads (downstream of Mud and Salt Sloughs, appendix B, table B5). Comprehensive monitoring data are not available to adequately determine selenium loss (that amount of load unaccounted for) after transit through the Grasslands wetlands (estimated annual maximum potential attenuation of 50 percent) (Presser and Piper, 1998).

Loads farther downstream in the San Joaquin River at Crows Landing/Patterson (table 5; appendix B, Table B6) and Vernalis (table 5; appendix B, table B7) show increases over loads measured at Mud and Salt Sloughs, and in some cases, over loads measured furthest upstream (Drainage Problem Area). The increases may be due to other sources of selenium entering the San Joaquin River or errors introduced through limitations of the data as noted above. During WYs 1986 to 1998, the loads in the San Joaquin River at Crows Landing/Patterson range from 3,064 to 15,501 lbs selenium with the maximum occurring in WY 1998 (appendix B, table B6). Selenium loads for the San Joaquin River at Vernalis from WYs 1986 to 1997 range from 3,558 to 17,238 lbs, with the

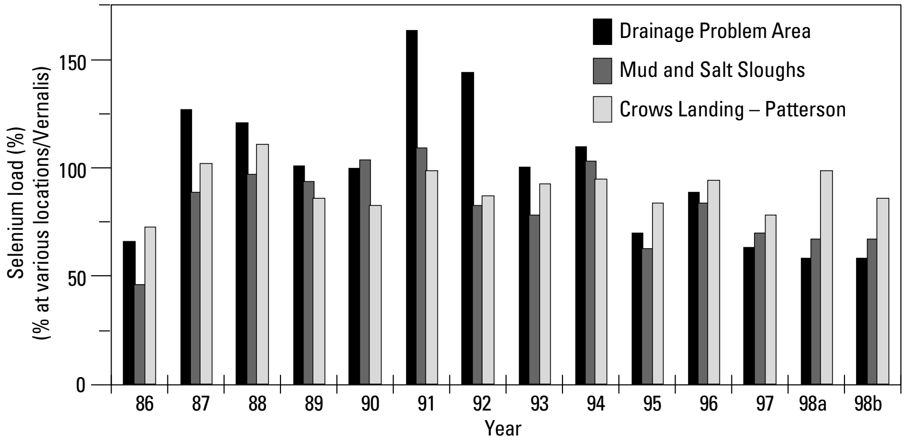

Figure D10. Percent selenium load (normalized to the selenium load at the San Joaquin River at Vernalis) for the Drainage Problem Area (DPA); combined Mud and Salt Sloughs (MS+SS); and the San Joaquin River at Crows Landing-Patterson (CL-PATT) for WY 1986 through WY 1997.

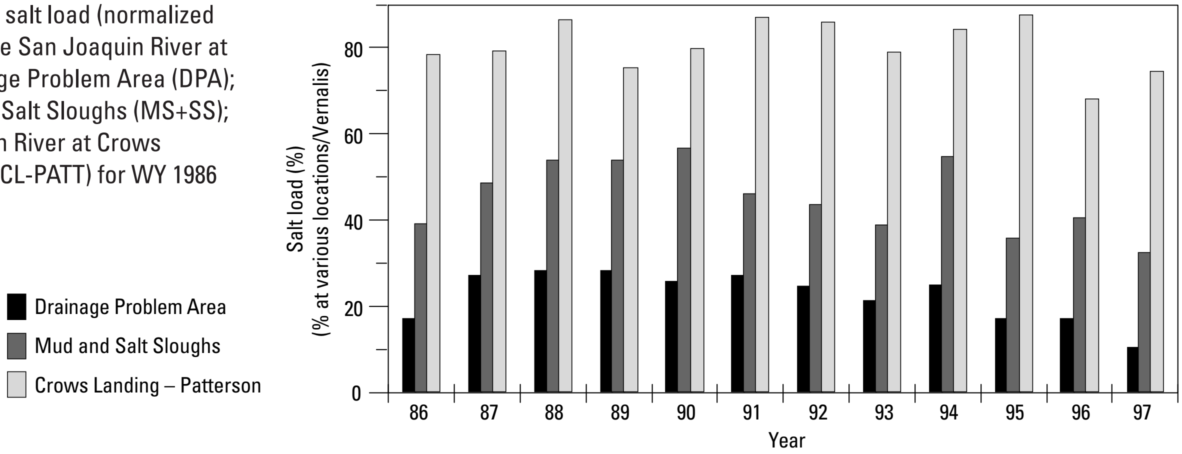

Figure D11. Percent salt load (normalized to the salt load at the San Joaquin River at Vernalis) for Drainage Problem Area (DPA); combined Mud and Salt Sloughs (MS+SS); and the San Joaquin River at Crows Landing-Patterson (CL-PATT) for WY 1986 through WY 1997.

two highest values occurring in 1986 and 1995 (appendix B, table B7). Two different load values were calculated for the San Joaquin River at Crows Landing for WY 1998 (15,501 lbs and 13,445 lbs) depending on sets of flow data. For WY 1998 for the San Joaquin River at Vernalis, the reported value is 15,810 lbs per year which is less than or similar to the value measured for the San Joaquin River at Crows Landing. A State limit for drainage of 8,000 lbs selenium from the Grassland Area was enacted in 1996.

Prediction of Short-Term Selenium Reservoirs

Data from WYs 1986 to 1994 from the Grassland area (or generically, the drainage source area) are given as an example of a managed agricultural drainage discharge system (Central Valley Board, 1996a, b, 1998d, e, f, g, h; Grassland Area Farmers, 1998b). Measurements for the drainage problem area are referenced to agricultural drainage canals for WYs 1986 to 1996 and site B (San Luis Drain discharge into Mud Slough) for WYs 1997 and 1998. Figures D12 through D14 show, using data from WYs 1986 to 1997, general relations among annualized amounts of:

- irrigation water applied to the drainage source area;
- flow generated from the drainage source area;

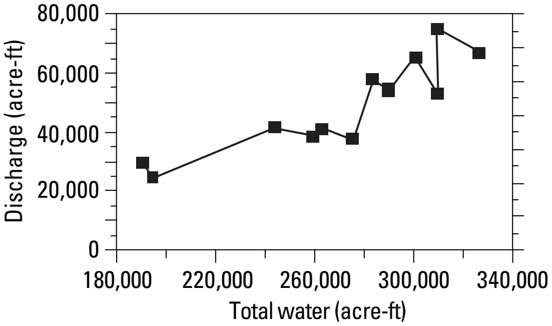

Figure D12. Relation between total water applied and drainage discharge for the Drainage Problem Area (DPA) during WY 1986 through WY 1997.

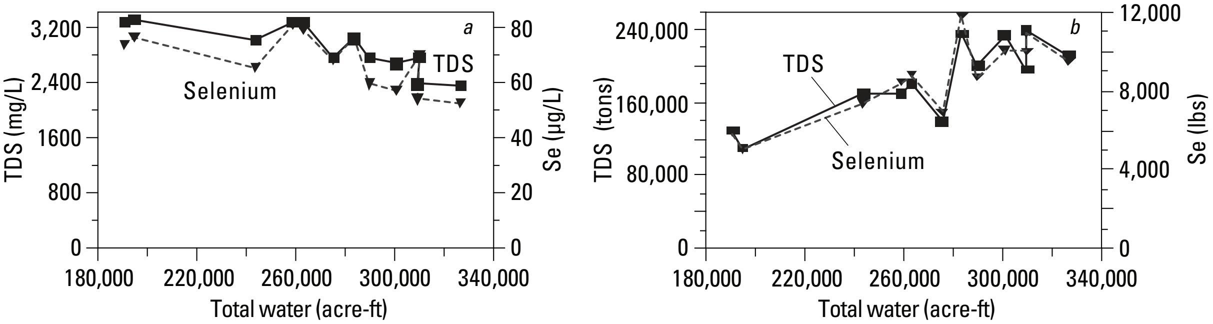

Figure D13. Relation among (*a*) total water applied, selenium concentration, and total dissolved solids concentration; (*b*) total water applied, selenium load, and salt load for the Drainage Problem Area (DPA) during WY 1986 through WY 1997.

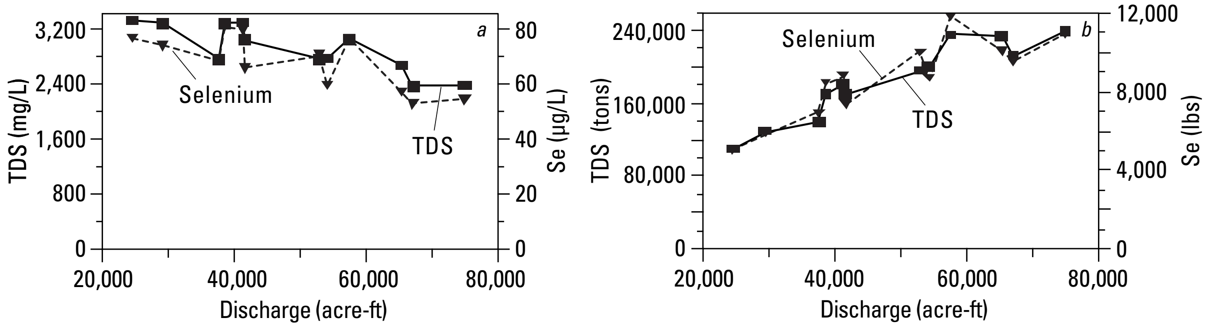

Figure D14. Relation among (*a*) drain discharge, selenium concentration, and total dissolved solids concentration; (*b*) drain discharge, selenium load, and salt load for the Drainage Problem Area (DPA) during WY 1986 through WY 1997.

- concentration of selenium in the generated discharge; and
- loads of salt and selenium generated from the drainage source area.

This series of figures illustrates some of the variables that affect load generation, but do not address the comprehensive processes controlling the distribution and transport of selenium and salt. Based on annualized data, figure D12 shows that as total water (applied irrigation water plus precipitation) increases, flow from the drainage source area increases. Figure D13 shows that as total applied water increases, selenium and salt concentrations in the discharge decrease. Figure D13 shows that as total applied water increases, selenium and salt loads from the drainage source area increase. Figure D14 shows that as flow from the drainage source area increases, selenium and salt concentrations decreases. Figure D14 shows that as flow from the drainage source area increases, selenium load increases.

However, based on monthly and daily data these annual relations change. Figures D15 and D16 show the relation among flow, concentration, and load using daily measurements for WYs 1997 and 1998 at the San Luis Drain discharge to Mud Slough (site B) (USBR and others, 1998, and ongoing). In WY 1997, selenium load and concentration increase with flow. In WY 1998 however, concentration and load decrease at flows greater than about 100 ft³/s, thus showing some drainage relief through dilution at the higher flows during storms in February 1998 (an El Nino year). [Note: These data have been generalized in the main text (fig. 6) to help denote the characteristics of source water in comparison to receiving water (also see discussion in main text)].

Figures D17 to D21 are a series of graphs that depict the relation between load, concentration, applied water, and flow for the San Luis Drain (site B) on a monthly basis. Figures D17 and D18 summarize monthly averages of flow, selenium load, and selenium concentration along with amounts of applied water (irrigation and precipitation) for WYs 1997 and 1998.

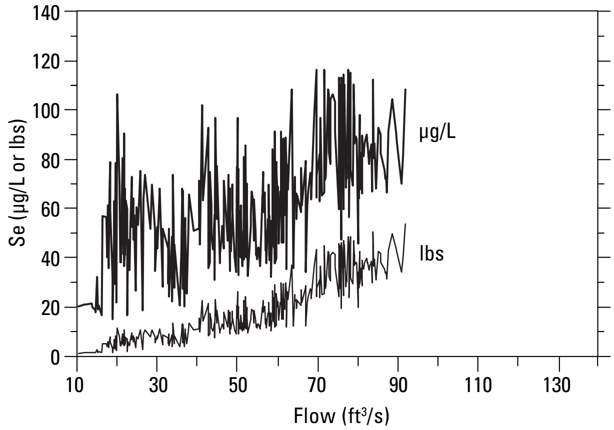

Figure D15. Relation among flow, selenium concentration, and selenium load on a daily basis at site B (San Luis Drain outflow to Mud Slough) for WY 1997.

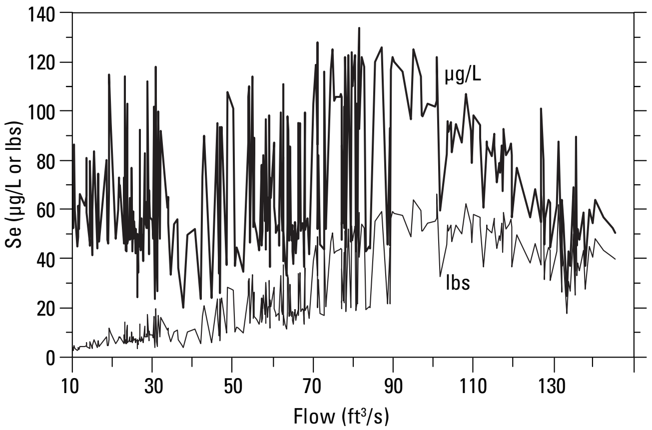

Figure D16. Relation among flow, selenium concentration, and selenium load on a daily basis at site B (San Luis Drain outflow to Mud Slough) for WY 1998.

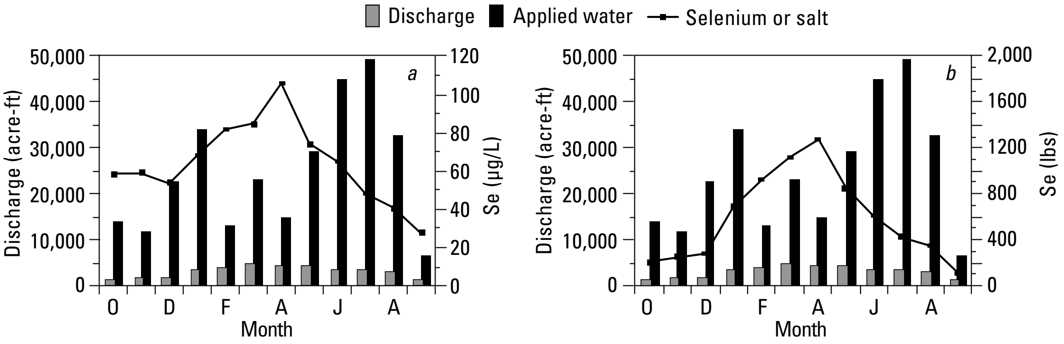

Figure D17. Relation among drainage discharge, applied water (irrigation/precipitation combined), and (*a*) selenium concentration; or (*b*) selenium load on a monthly basis at site B (San Luis Drain outflow to Mud Slough) during WY 1997.

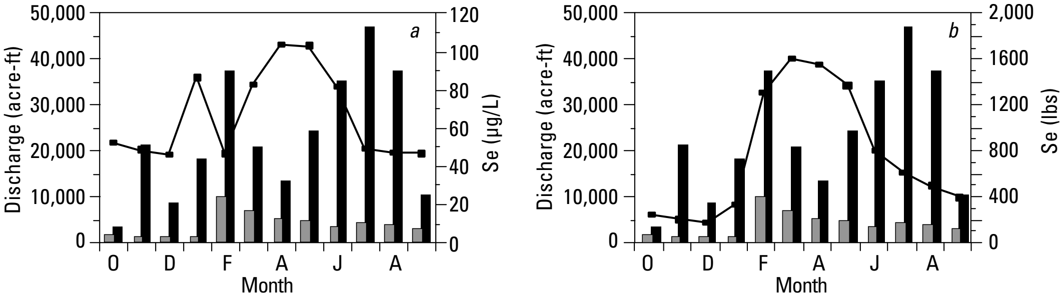

Figure D18. Relation among drainage discharge, applied water (irrigation/precipitation combined), and (*a*) selenium concentration; or (*b*) selenium load on a monthly basis at site B (San Luis Drain outflow to Mud Slough) during WY 1998.

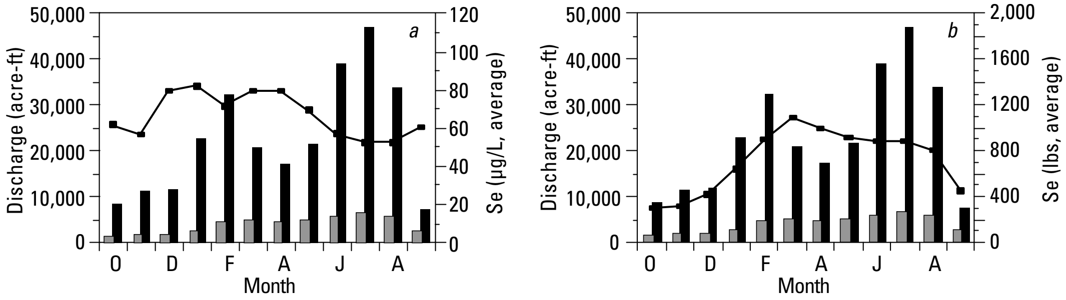

Figure D19. Relation among drainage discharge, applied water (irrigation/precipitation combined), and (*a*) selenium concentration; or (*b*) selenium load on a monthly basis at site B (San Luis Drain outflow to Mud Slough) for base average WY 1986 through WY 1994.

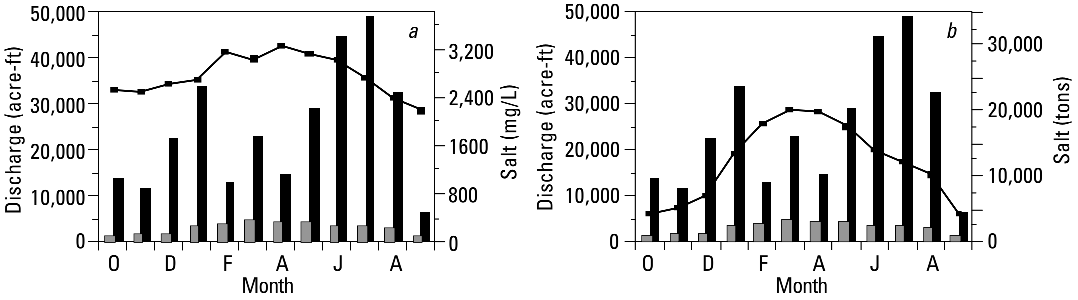

Figure D20. Relation among drainage discharge, applied water (irrigation/precipitation combined), and (*a*) salt concentration; or (*b*) salt load on a monthly basis at site B (San Luis Drain outflow to Mud Slough) during WY 1997.

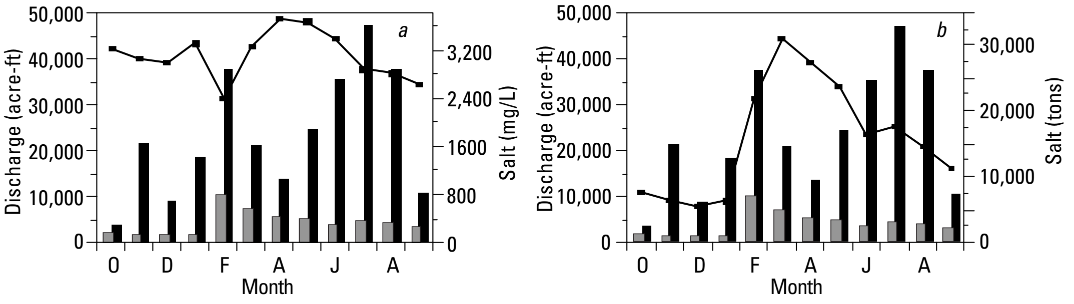

Figure D21. Relation among drainage discharge, applied water (irrigation/precipitation combined), and (*a*) salt concentration; or (*b*) salt load on a monthly basis at site B (San Luis Drain outflow to Mud Slough) during WY 1998.

Figure D19 shows monthly averages for WYs 1986 through 1994 (the base year average used for generating Grassland Bypass Channel Project load targets, see appendix B, figure B1) for the same parameters. For comparison, figures D20 and D21 summarize salt load and salt concentrations for the San Luis Drain (site B) in a similar series of graphs to that for selenium load in WYs 1997 and 1998. Patterns for the San Luis Drain discharge are similar through the series of graphs, showing peak selenium loads and concentrations during the months of March or April. Maximum application of water occurs in June, July, and August. Winter rainfall peaks can be seen especially in WY 1998 during February.

Appendix E. Sediment Quantity and Quality Tables

Table E1. Quantity of sediment (bed and suspended), selenium concentrations, and selenium loads in bed sediment of the original San Luis Drain.

San Luis Drain sediment survey (segment and date)	Deposition (tons/year, dry weight)	Volume (cubic yards, dry weight)	Selenium load (lbs)	Selenium range/average (µg/g, dry weight)	Suspended sediment (average input) (mg/L)	Suspended sediment (average output) (mg/L)	Reference
28-mile segment, 1984	–	80,583	–	–	–	–	USBR, 1986
85-mile segment, compilation of five surveys since August, 1984	–	211,000	5,280	5–190/84	–	–	USBR, 1986
Compilation of five surveys, 1984-1993	–	–	–	1.4–210/55	–	–	Presser and others, 1996
28-mile segment, 1987 28-mile segment, 1997 28-mile segment, 1998 28-mile segment, 1999 28-mile segment, 2000 28-mile segment, 2001 28-mile segment, 2002	–	58,094 60,594 82,406 88,621 114,368 135,809 158,489	–	–	–	–	USBR and others, 1998 and ongoing
Segments 1 and 10; February and May, 1994	–	–	–	2.4-94/39			Presser and others, 1996; Presser and Piper, 1998
Segments 1, 10, 17, 24; August, 1994	–	–	–	3.2–110/43	–	–	Presser and others, 1996; Presser and Piper, 1998
Segments 1/2, 10/11, 15/16, 27/28; September, 1994	–	–	–	11–94/44	–	–	Presser and others, 1996; Presser and Piper, 1998
28-mile segment, 1995	–	55,788	4,500[a]	–	–	–	Presser and Piper, 1998
85-mile segment, 1995	–	177,900	14,400[a]	–	–	–	Presser and Piper, 1998
28-mile segment, 1997	–	60,593	–	2.9–100/30 (whole core average except 0.1 value)	–	–	USBR and others, 1998 and ongoing
Estimated from suspended solids, water-year 1997	465	308 (1.8 g/cm^3) 213 (2.6 g/cm^3)	–	–	102	28	USBR and others, 1998 and ongoing

[a] Calculated using an average selenium concentration in bed sediment of 44 µg/g dry weight (see 1994 data above).

Table E2. Selenium in sediment (bed and suspended) and plankton in natural channels.

[All values are dry weight. Natural channels are subjected to intermittent agricultural drainage discharge from the Grassland Drainage Problem Area through: (a) the Agatha Canal and Camp 13 Slough from the 1950s to September 1996; and (b) the San Luis Drain from October 1996 and continuing. Data sources: Department of Fish and Game = White and others, 1987, 1988, 1989; Urquhart and Regalado, 1991; USFWS = Henderson and others, 1995; USBR = 1995; USBR and others, 1998 and ongoing.]

Location, date, and reference	Bed sediment (µg/g)	Suspended sediment (µg/g)	Plankton (µg/g)
Agatha Canal (Department of Fish and Game)			
1988	1.0	1.4	3.8
Camp 13 Slough (Department of Fish and Game)			
1987	0.79	–	–
1988	0.71–.4	1.6–2.6	0.54–3.6
1989	0.89	3.2	3.2
East Big Lake impoundment (USFWS)			
1992–1993	1.0–1.8	–	–
Mud Slough , 200m downstream of San Luis Drain (inactive)[a] (Department of Fish and Game)			
1987	0.32–1.3	2.1	–
1988	0.31–1.8	1.2–6.7	0.19–3.4
1989	1.1	2.4	3.8
Mud Slough, 600 yards upstream of San Luis Drain (SLD) discharge; immediately downstream (120 m) of SLD (inactive) [a]; 6.6 miles downstream of SLD (inactive) [a] (USFWS)			
1992–1993 (average of all sites)	0.15–0.75	–	–
Mud Slough upstream of San Luis Drain discharge (USBR)			
1993–September, 1995	<0.1–0.3	–	–
Water-year 1997	<0.10–0.44	–	–
Mud Slough immediately downstream of San Luis Drain (USBR; Department of Fish and Game)			
1993–-September, 1995 (inactive)[a]	<0.1–0.4	–	–
Water-year 1997	<0.10–0.76		–
Mud Slough 6.6 miles downstream of San Luis Drain (Department of Fish and Game; USBR and others)			
1993–September, 1996 (inactive)[a]	<0.1–0.7	–	–
Water-year 1997	0.70–1.9	–	–
Mud Slough 6.6 miles downstream of San Luis Drain (Department of Fish and Game; USBR and others)			
1993–1995	0.3–0.6	–	–
March, 1997	0.4–1.5	–	–
Salt Slough near highway 165 (Department of Fish and Game)			
1987	0.31–1.3	1.4	–
1988	1.1–1.4	1.2–2.6	0.17–4.2
1989	1.5	2.0	5.0
Salt Slough (USFWS; USBR; USBR and others)			
1992–1993	0.2–0.45	–	–
1993–September, 1995	0.2–1.3	–	–
Water-year 1997	0.12–0.94	–	–
San Joaquin River at Lander Avenue (upstream of discharge) (Department of Fish and Game)			
1987	0.01	0.98	–
1988	0.04–<0.18	1.0–1.8	<0.08–0.16
1989	<0.18	2.0	0.23
San Joaquin River at or below Merced River (Department of Fish and Game)			
1987	0.19–0.75	1.7	–
1988	<0.18–0.56	1.3–2.2	0.33–2.0
1989	0.18	1.9	2.5
San Joaquin River at Vernalis (Airport Blvd.; Maze Blvd; all below Stanislaus River) (Department of Fish and Game)			
1987	0.25–1.2	1.2	–
1988	<0.18–5.2	0.91–2.4	0.11–2.1
1989	–	1.4	1.2

[a] The San Luis Drain was not in use (inactive) from July 1,1986 to September 23, 1996.

[b] Data from 2002 through 2003 indicate selenium concentrations in bed sediment (0-3 cm) of 5 to 8.5 µg/g dry weight in a seasonal backwater (site I2) of the Grassland Bypass Channel Project (USBR and others, 1998 and ongoing).

Appendix F. Supplemental Spreadsheets

Tables

Table F1. Forecasts of monthly composite freshwater endmember concentrations of selenium assuming that all San Joaquin River inflow enters the Bay-Delta, all freshwater exports are from the Sacramento River, and a selenium concentration of 2 µg/L is maintained in the San Joaquin River.

[A total of 36,848 lbs selenium is released annually. Flow data are from 1997. This table is a representation of a spreadsheet.]

Restoration scenario	Volume (average ft^3/s)	Volume (million acre-ft)	Volume (billion liters)	Selenium				
				Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (17.5 psu) (µg/L)
January								
Total outflow index	256,565							
Sacramento River	224,096	13.31	16,412.84	0.04	657	1,448		
San Joaquin River	32,469	1.93	2,378.04	2	4,756	10,492		
San Luis Drain	0	0.00	0.00	62.5	0	0		
Refineries	–	0.00	1.03	50	51	113		
Total						12,054	0.29	0.15
February								
Total outflow index	119,090							
Sacramento River	86,950	5.16	6,368.24	0.04	255	562		
San Joaquin River	32,140	1.91	2,353.94	2	4,708	10,386		
San Luis Drain	0	0.00	0.00	62.5	0	0		
Refineries	–	0.00	1.03	50	51	113		
Total						11,061	0.57	0.29
March								
Total outflow index	33,831							
Sacramento River	20,944	1.24	1,533.94	0.04	61	135		
San Joaquin River	12,887	0.77	943.85	2	1,888	4,164		
San Luis Drain	0	0.00	0.00	62.5	0	0		
Refineries	–	0.00	1.03	50	51	113		
Total						4,413	0.81	0.40
April								
Total outflow index	13,734							
Sacramento River	9,811	0.58	718.56	0.04	29	63		
San Joaquin River	3,923	0.23	287.32	2	575	1,268		
San Luis Drain	0	0.00	0.00	62.5	0	0		
Refineries	–	0.00	1.03	50	51	113		
Total						1,444	0.65	0.33
May								
Total outflow index	12,261							
Sacramento River	7,210	0.43	528.06	0.04	21	47		
San Joaquin River	5,051	0.30	369.94	2	740	1,632		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						1,792	0.90	0.45

Table F1. Forecasts of monthly composite freshwater endmember concentrations of selenium assuming that all San Joaquin River inflow enters the Bay-Delta, all freshwater exports are from the Sacramento River, and a selenium concentration of 2 µg/L is maintained in the San Joaquin River—Continued.

[A total of 36,848 lbs selenium is released annually. Flow data are from 1997. This table is a representation of a spreadsheet.]

Restoration scenario	Volume (average ft^3/s)	Volume (million acre-ft)	Volume (billion liters)	Selenium				
				Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (17.5 psu) (µg/L)
June								
Total outflow index	8,762							
Sacramento River	5,550	0.33	406.48	0.04	16	36		
San Joaquin River	3,212	0.19	235.25	2	470	1,038		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						1,187	0.84	0.42
July								
Total outflow index	9,350							
Sacramento River	7,326	0.44	536.56	0.04	21	47		
San Joaquin River	2,024	0.12	148.24	2	296	654		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						815	0.54	0.27
August								
Total outflow index	9,031							
Sacramento River	7,378	0.44	540.37	0.04	22	48		
San Joaquin River	1,653	0.10	121.07	2	242	534		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						695	0.48	0.24
September								
Total outflow index	4,555							
Sacramento River	2,633	0.16	192.84	0.04	8	17		
San Joaquin River	1,922	0.11	140.77	2	282	621		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						751	1.02	0.51
October								
Total outflow index	4,571							
Sacramento River	2,237	0.13	163.84	0.04	7	14		
San Joaquin River	2,334	0.14	170.94	2	342	754		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						882	1.19	0.60

Table F1. Forecasts of monthly composite freshwater endmember concentrations of selenium assuming that all San Joaquin River inflow enters the Bay-Delta, all freshwater exports are from the Sacramento River, and a selenium concentration of 2 µg/L is maintained in the San Joaquin River—Continued.

[A total of 36,848 lbs selenium is released annually. Flow data are from 1997. This table is a representation of a spreadsheet.]

Restoration scenario	Volume (average ft³/s)	Volume (million acre-ft)	Volume (billion liters)	Selenium				
				Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (17.5 psu) (µg/L)
November								
Total outflow index	6,270							
Sacramento River	4,095	0.24	299.92	0.04	12	26		
San Joaquin River	2,175	0.13	159.30	2	319	703		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	0.00	1.03	50	51	113		
Total						843	0.83	0.41
December								
Total outflow index	18,914							
Sacramento River	16,780	1.00	1,228.97	0.04	49	108		
San Joaquin River	2,134	0.13	156.29	2	313	690		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	0.00	1.03	50	51	113		
Total						911	0.30	0.15
Total Selenium Exported from San Joaquin River (lbs)						36,848		

Table F2. Forecasts of monthly composite freshwater endmember concentrations of selenium assuming that all San Joaquin River inflow enters the Bay-Delta, all freshwater exports are from the Sacramento River, and a selenium concentration of 1 µg/L is maintained in the San Joaquin River.

[A total of 20,380 lbs selenium is released annually. Flow data are from 1997. This table is a representation of a spreadsheet.]

Restoration scenario	Volume (average ft^3/s)	Volume (million acre-ft)	Volume (billion liters)	Selenium				
				Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (17.5 psu) (µg/L)
January								
Total outflow index	256,565							
Sacramento River	224,096	13.31	16,412.84	0.04	657	1,448		
San Joaquin River	32,469	1.93	2,378.04	1	2,378	5,246		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113	0.16	0.08
Total						6,808		
February								
Total outflow index	119,090							
Sacramento River	86,950	5.16	6,368.24	0.04	255	562		
San Joaquin River	32,140	1.91	2,353.94	1	2,354	5,193		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						5,868	0.30	0.15
March								
Total outflow index	33,831							
Sacramento River	20,944	1.24	1,533.94	0.04	61	135		
San Joaquin River	12,887	0.77	943.85	1	944	2,082		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						2,331	0.43	0.21
April								
Total outflow index	13,734							
Sacramento River	9,811	0.58	718.56	0.04	29	63		
San Joaquin River	3,923	0.23	287.32	1	287	634		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						811	0.36	0.18
May								
Total outflow index	12,261							
Sacramento River	7,210	0.43	528.06	0.04	21	47		
San Joaquin River	5,051	0.30	369.94	1	370	816		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						976	0.49	0.25

Table F2. Forecasts of monthly composite freshwater endmember concentrations of selenium assuming that all San Joaquin River inflow enters the Bay-Delta, all freshwater exports are from the Sacramento River, and a selenium concentration of 1 µg/L is maintained in the San Joaquin River—Continued.

[A total of 20,380 lbs selenium is released annually. Flow data are from 1997. This table is a representation of a spreadsheet.]

Restoration scenario	Volume (average ft^3/s)	Volume (million acre-ft)	Volume (billion liters)	Selenium				
				Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (17.5 psu) (µg/L)
June								
Total outflow index	8,762							
Sacramento River	5,550	0.33	406.48	0.04	16	36		
San Joaquin River	3,212	0.19	235.25	1	235	519		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						668	0.47	0.24
July								
Total outflow index	9,350							
Sacramento River	7,326	0.44	536.56	0.04	21	47		
San Joaquin River	2,024	0.12	148.24	1	148	327		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						488	0.32	0.16
August								
Total outflow index	9,031							
Sacramento River	7,378	0.44	540.37	0.04	22	48		
San Joaquin River	1,653	0.10	121.07	1	121	267		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						428	0.29	0.15
September								
Total outflow index	4,555							
Sacramento River	2,633	0.16	192.84	0.04	8	17		
San Joaquin River	1,922	0.11	140.77	1	141	311		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						441	0.60	0.30
October								
Total outflow index	4,571							
Sacramento River	2,237	0.13	163.84	0.04	7	14		
San Joaquin River	2,334	0.14	170.94	1	171	377		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						505	0.68	0.34

Table F2. Forecasts of monthly composite freshwater endmember concentrations of selenium assuming that all San Joaquin River inflow enters the Bay-Delta, all freshwater exports are from the Sacramento River, and a selenium concentration of 1 µg/L is maintained in the San Joaquin River—Continued.

[A total of 20,380 lbs selenium is released annually. Flow data are from 1997. This table is a representation of a spreadsheet.]

Restoration scenario	Volume (average ft^3/s)	Volume (million acre-ft)	Volume (billion liters)	Selenium				
				Concentration (µg/L)	Load (billion µg)	Load (lbs per six months)	Freshwater endmember (µg/L)	Carquinez Strait (17.5 psu) (µg/L)
November								
Total outflow index	6,270							
Sacramento River	4,095	0.24	299.92	0.04	12	26		
San Joaquin River	2,175	0.13	159.30	1	159	351		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						491	0.48	0.24
December								
Total outflow index	18,914							
Sacramento River	16,780	1.00	1,228.97	0.04	49	108		
San Joaquin River	2,134	0.13	156.29	1	156	345		
San Luis Drain	0	0.00	0.00	0	0	0		
Refineries	–	–	1.03	50	51	113		
Total						567	0.19	0.09
Total Selenium Exported from San Joaquin River (lbs)						20,380		

Table F3. Forecasts of particulate selenium concentration for a wet year in a high flow season under load scenarios for conveyance of agricultural drainage either through a San Luis Drain extension or the San Joaquin River.

[Inputs from the Sacramento River and oil refineries also are considered. Refinery cleanup is assumed in all scenarios. Scenarios using a San Luis Drain extension for conveyance assume a 2 million acre-ft inflow from the San Joaquin River reaches the Bay Delta. The *targeted* scenario using the San Joaquin River for conveyance assumes no San Luis Drain inflow and a 1.1 million acre ft inflow reaches the Bay-Delta. The *restoration* scenario assumes greater San Joaquin River inflows with the high flow season conveying 75% of the annual river flow to the Bay-Delta. This table is a representation of a spreadsheet.]

		Selenium									
	Volume (million acre-ft)	Load (lbs per six months)	Source concentration (µg/L)	Dissolved concentration		Particulate concentration					
						K_d=1,000		K_d=3,000		K_d=10,000	
				Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup.											
Sacramento R.	17	1,850	0.04								
San Joaquin R.	2	5,440	1								
San Luis Drain	0.05	6,800	50								
Refineries	0.005	680	50								
				0.28	0.14	0.280	0.140	0.840	0.420	2.800	1.400
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup.											
Sacramento R.	17	1,850	0.04								
San Joaquin R.	2	5,440	1								
San Luis Drain	0.11	18,700	62.5								
Refineries	0.005	680	50								
				0.51	0.26	0.510	0.260	1.530	0.780	5.100	2.600
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup.											
Sacramento R.	17	1,850	0.04								
San Joaquin R.	2	5,440	1								
San Luis Drain	0.11	44,820	150								
Refineries	0.005	680	50								
				1.02	0.51	1.020	0.510	3.060	1.530	10.200	5.100
Load scenario: San Luis Drain extension at 300 ft^3/s and 300 µg/L for a load of 89,760 lbs per six months; refinery cleanup.											
Sacramento R.	17	1,850	0.04								
San Joaquin R.	2	5,440	1								
San Luis Drain	0.11	89,760	300								
Refineries	0.005	680	50								
				1.88	0.94	1.880	0.940	5.640	2.820	18.800	9.400
Load scenario: *Targeted* San Joaquin River load of 7,180 lbs annually (3,590 lbs per six months); refinery cleanup.											
Sacramento R.	17	1,850	0.04								
San Joaquin R.	1.1	3,590	1.2								
San Luis Drain	0	0	0								
Refineries	0.005	680	50								
				0.12	0.06	0.120	0.060	0.360	0.180	1.200	0.600
Load scenario: San Joaquin River Restoration (conveys 75% of San Joaquin River inflow); refinery cleanup.											
Sacramento R.	17	1,850	0.04								
San Joaquin R.	2.25	3,060	0.5								
San Luis Drain	0	0	0								
Refineries	0.005	680	50								
				0.11	0.05	0.110	0.050	0.330	0.150	1.100	0.500

Table F4. Forecasts of particulate selenium concentration for a wet year in a low flow season under load scenarios for conveyance of agricultural drainage either through a San Luis Drain extension or the San Joaquin River.

[Inputs from the Sacramento River and oil refineries also are considered. Refinery cleanup is assumed in all scenarios. Scenarios using a San Luis Drain extension for conveyance assume a 2 million acre-ft inflow from the San Joaquin River reaches the Bay Delta. The *targeted* scenario using the San Joaquin River for conveyance assumes no San Luis Drain inflow and a 1.1 million acre ft inflow reaches the Bay-Delta. The *restoration* scenario assumes greater San Joaquin River inflows with the low flow season conveying 25% of the annual river flow to the Bay-Delta. This table is a representation of a spreadsheet.]

	Volume (million acre-ft)	Selenium									
		Load (lbs per six months)	Source concentration (µg/L)	Dissolved concentration		Particulate concentration					
						K_d=1,000		K_d=3,000		K_d=10,000	
				Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup.											
Sacramento R.	2.3	250	0.04								
San Joaquin R.	0.001	3	2								
San Luis Drain	0.05	6,800	50								
Refineries	0.005	680	50								
				1.21	0.60	1.210	0.600	3.630	1.800	12.100	6.000
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup.											
Sacramento R.	2.3	250	0.04								
San Joaquin R.	0.001	5	2								
San Luis Drain	0.11	18,700	62.5								
Refineries	0.005	680	50								
				2.99	1.49	2.990	1.490	8.970	4.470	29.900	14.900
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup.											
Sacramento R.	2.3	250	0.04								
San Joaquin R.	0.001	5	2								
San Luis Drain	0.11	44,820	150								
Refineries	0.005	680	50								
				6.97	3.49	6.970	3.490	20.910	10.470	69.700	34.900
Load scenario: San Luis Drain extension at 300 ft^3/s and 300 µg/L for a load of 89,760 lbs per six months; refinery cleanup.											
Sacramento R.	2.3	250	0.04								
San Joaquin R.	0.001	5	2								
San Luis Drain	0.11	89,760	300								
Refineries	0.005	680	50								
				13.8	6.9	13.800	6.900	41.400	20.700	138.000	69.000
Load scenario: *Targeted* San Joaquin River load of 6,800 lbs annually (3,400 lbs per six months); refinery cleanup.											
Sacramento R.	2.3	250	0.04								
San Joaquin R.	0.5	3,400	2.5								
San Luis Drain	0	0	0								
Refineries	0.005	680	50								
				0.57	0.28	0.570	0.280	1.710	0.840	5.700	2.800
Load scenario: San Joaquin River Restoration (conveys 75% of San Joaquin River inflow); refinery cleanup											
Sacramento R.	2.3	250	0.04								
San Joaquin R.	0.75	1,020	0.5								
San Luis Drain	0	0	0								
Refineries	0.005	680	50								
				0.23	0.12	0.230	0.120	0.690	0.360	2.300	1.200

Table F5. Forecasts of particulate selenium concentration for a critically dry year in a low flow season under load scenarios for conveyance of agricultural drainage either through a San Luis Drain extension or the San Joaquin River.

[Inputs from the Sacramento River and oil refineries also are considered. Refinery cleanup is assumed in all scenarios. Scenarios using a San Luis Drain extension for conveyance assume a 2 million acre-ft inflow from the San Joaquin River reaches the Bay Delta. The *targeted* scenario using the San Joaquin River for conveyance assumes no San Luis Drain inflow and a 0.5 million acre ft inflow reaches the Bay-Delta. The *restoration* scenario assumes greater San Joaquin River inflows with the low flow season conveying 25% of the annual river flow to the Bay-Delta. This table is a representation of a spreadsheet.]

	Volume (million acre-ft)	Selenium								
		Load (lbs per six months)	Source concentration (µg/L)	Dissolved concentration		Particulate concentration				
						K_d=1,000		K_d=3,000		K_d=10,000	
				Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup.										
Sacramento R.	1.3	141	0.04							
San Joaquin R.	0.0005	3	2							
San Luis Drain	0.05	6,800	50							
Refineries	0.005	680	50							
				2.07	1.03	2.070	1.030	6.210	3.090	20.700	10.300
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup.										
Sacramento R.	1.3	141	0.04							
San Joaquin R.	0.0005	3	2							
San Luis Drain	0.11	18,700	62.5							
Refineries	0.005	680	50							
				5.07	2.54	5.070	2.540	15.210	7.620	50.700	25.400
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup.										
Sacramento R.	1.3	141	0.04							
San Joaquin R.	0.001	5	2							
San Luis Drain	0.11	44,880	150							
Refineries	0.005	680	50							
				11.87	5.93	11.870	5.930	35.610	17.790	118.700	59.300
Load scenario: San Luis Drain extension at 300 ft^3/s and 300 µg/L for a load of 89,760 lbs per six months; refinery cleanup.										
Sacramento R.	1.3	141	0.04							
San Joaquin R.	0.0005	3	2							
San Luis Drain	0.11	89,760	300							
Refineries	0.005	680	50							
				23.53	11.76	23.530	11.760	70.590	35.280	235.300	117.600
Load scenario: *Targeted* San Joaquin River load of 6,800 lbs annually (3,400 lbs per six months); refinery cleanup.										
Sacramento R.	2.3	250	0.04							
San Joaquin R.	0.5	3,400	2.5							
San Luis Drain	0	0	0							
Refineries	0.005	680	50							
				0.86	0.43	0.860	0.430	2.580	1.290	8.600	4.300
Load scenario: San Joaquin River Restoration (conveys 25% of San Joaquin River inflow); refinery cleanup										
Sacramento R.	1.6	174	0.04							
San Joaquin R.	0.28	381	0.5							
San Luis Drain	0	0	0							
Refineries	0.005	680	50							
				0.24	0.12	0.240	0.120	0.720	0.360	2.400	1.200

Table F6. Bioaccumulation of selenium by a generic bivalve (ingestion rate, IR=0.25 g food/g tissue/day; efflux rate, k_e=0.03/day) for a wet year in a high flow season under various load scenarios, partitioning coefficients (K_d=1,000; 3,000; 10,000), particulate selenium concentrations, and assimilation efficiencies (AE1=0.35; AE2=0.55; AE3=0.63; AE4=0.8).

[This table is a representation of a spreadsheet.]

	Selenium					
	K_d =1,000		K_d =3,000		K_d =10,000	
	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup.						
Particles	0.280	0.140	0.840	0.420	2.800	1.400
AE1	0.8	0.4				
AE2			3.9	1.9		
AE3					14.7	7.4
AE4					18.7	9.3
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup.						
Particles	0.510	0.260	1.530	0.780	5.100	2.600
AE1	1.5	0.8				
AE2			7.0	3.6		
AE3					26.8	13.7
AE4					34.0	17.3
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup.						
Particles	1.020	0.510	3.060	1.530	10.200	5.100
AE1	3.0	1.5				
AE2			14.0	7.0		
AE3					53.6	26.8
AE4					68.0	34.0
Load scenario: Prior to refinery cleanup: no San Luis Drain extension						
Particles	0.220	0.110	0.660	0.330	2.180	1.100
AE1	0.96	0.48				
AE2			4.54	2.27		
AE3					17.17	8.66
AE4					21.80	11.00

Table F7. Bioaccumulation of selenium by a generic bivalve (ingestion rate, IR=0.25g food/g tissue/day; efflux rate, k_e=0.03/day) for a wet year in a low flow season under various load scenarios, partitioning coefficients (K_d=1,000; 3,000; 10,000), particulate selenium concentrations, and assimilation efficiencies (AE1=0.35; AE2=0.55; AE3=0.63; AE4=0.8).

[This table is a representation of a spreadsheet.]

	Selenium					
	K_d =1,000		**K_d =3,000**		**K_d =10,000**	
	Endmember (µg/L)	**Carquinez Strait (µg/L)**	**Endmember (µg/L)**	**Carquinez Strait (µg/L)**	**Endmember (µg/L)**	**Carquinez Strait (µg/L)**
Load scenario: San Luis Drain extension at 150 ft³/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup.						
Particles	1.210	0.600	3.630	1.800	12.100	6.000
AE1	3.5	1.8				
AE2			16.6	8.3		
AE3					63.5	47.3
AE4					80.7	60.0
Load scenario: San Luis Drain extension at 300 ft³/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup.						
Particles	2.990	1.490	8.970	4.470	29.900	14.900
AE1	8.7	4.3				
AE2			41.1	20.5		
AE3					157.0	117.3
AE4					199.3	149.0
Load scenario: San Luis Drain extension at 300 ft³/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup.						
Particles	6.970	3.490	20.910	10.470	69.700	34.900
AE1	20.3	10.2				
AE2			95.8	48.0		
AE3					365.9	274.8
AE4					464.7	349.0
Load scenario: Prior to refinery cleanup: no San Luis Drain extension						
Particles	0.390	0.200	1.170	0.600	3.900	2.000
AE1	1.7	0.9				
AE2			8.0	4.1		
AE3					30.7	15.8
AE4					39.0	20.0

Table F8. Bioaccumulation of selenium by a generic bivalve (ingestion rate, IR=0.25 g food/g tissue/day; efflux rate, k_e=0.03/day) for a critically dry year in a low flow season under various load scenarios, partitioning coefficients (K_d=1,000; 3,000; 10,000), particulate selenium concentrations, and assimilation efficiencies (AE1=0.35; AE2=0.55; AE3=0.63; AE4=0.8).

[This table is a representation of a spreadsheet.]

	Selenium					
	K_d =1,000		K_d =3,000		K_d =10,000	
	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)	Endmember (µg/L)	Carquinez Strait (µg/L)
Load scenario: San Luis Drain extension at 150 ft^3/s and 50 µg/L for a load of 6,800 lbs per six months; refinery cleanup.						
Particles	2.100	1.000	6.200	3.100	20.700	10.300
AE1	6.1	2.9				
AE2			28.4	14.2		
AE3					108.7	81.1
AE4					138.0	103.0
Load scenario: San Luis Drain extension at 300 ft^3/s and 62.5 µg/L for a load of 18,700 lbs per six months; refinery cleanup.						
Particles	5.100	2.500	15.200	7.600	50.700	25.400
AE1	14.9	7.3				
AE2			69.7	34.8		
AE3					266.2	200.0
AE4					338.0	254.0
Load scenario: San Luis Drain extension at 300 ft^3/s and 150 µg/L for a load of 44,880 lbs per six months; refinery cleanup.						
Particles	11.900	5.900	35.600	17.800	119.000	59.000
AE1	34.7	17.2				
AE2			163.2	81.6		
AE3					624.8	464.6
AE4					793.3	590.0
Load scenario: Prior to refinery cleanup: no San Luis Drain extension						
Particles	0.530	0.270	1.590	0.810	5.300	2.700
AE1	2.3	1.2				
AE2			10.9	5.6		
AE3					41.7	21.3
AE4					53.0	27.0

Table F9. Bioaccumulation of selenium by a generic bivalve (ingestion rate, IR=0.25 g food/g tissue/day; efflux rate, k_e=0.03/day) for a *targeted* San Joaquin River load scenario (approximately 7,000 lbs selenium annually or 3,400 or 3,590 lbs selenium in six months depending on flow season) for a critically dry year in a low flow season, a wet year in a low flow season, and a wet year in a high flow season under various partitioning coefficients (K_d=1,000; 3,000; 10,000), particulate selenium concentrations, and assimilation efficiencies (AE1=0.35; AE2=0.55; AE3=0.63; AE4=0.8).

[This table is a representation of a spreadsheet.]

	Selenium					
	K_d =1,000		**K_d =3,000**		**K_d =10,000**	
	Endmember (µg/L)	**Carquinez Strait (µg/L)**	**Endmember (µg/L)**	**Carquinez Strait (µg/L)**	**Endmember (µg/L)**	**Carquinez Strait (µg/L)**
Critically dry year in a low flow season						
Particles	0.860	0.430	2.580	1.290	8.600	4.300
AE1	2.5	1.3				
AE2			11.8	5.9		
AE3					45.2	33.9
AE4					57.3	43.0
Wet year in a low flow season						
Particles	0.570	0.280	1.710	0.840	5.700	2.800
AE1	1.7	0.8				
AE2			7.8	3.9		
AE3					29.9	22.1
AE4					38.0	28.0
Wet year in a high flow season						
Particles	0.120	0.060	0.360	0.180	1.200	0.600
AE1	0.4	0.2				
AE2			1.7	0.8		
AE3					6.3	4.7
AE4					8.0	6.0

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