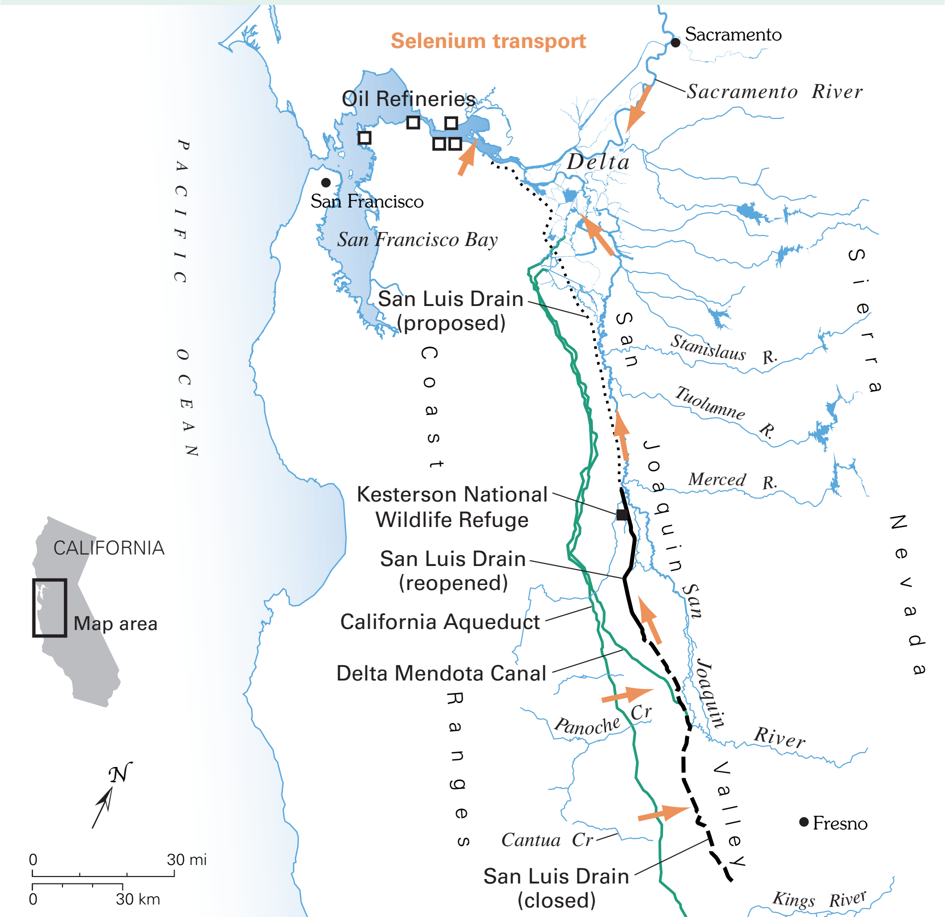
Linking Selenium Sources to Ecosystems: San Francisco Bay-Delta Model

Marine sedimentary rocks of the Coast Ranges contribute selenium to soil, surface water, and ground water in the western San Joaquin Valley, California. Irrigation funnels selenium into a network of subsurface drains and canals. Proposals to build a master drain (i.e., San Luis Drain) to discharge into the San Francisco Bay-Delta Estuary remain as controversial today as they were in the 1950s, when drainage outside the San Joaquin Valley was first considered. An existing 85-mile portion of the San Luis Drain was closed in 1986 after fish mortality and deformities in ducks, grebes and coots were discovered at Kesterson National Wildlife Refuge, the temporary terminus of the drain. A 28-mile portion of the drain now conveys drainage from 100,000 acres into the San Joaquin River and eventually into the Bay-Delta. If the San Luis Drain is extended directly to the Bay-Delta, as is now being proposed as an alternative to sustain agriculture, it could receive drainage from an estimated one-million acres of farmland affected by rising water tables and increasing salinity. In addition to agricultural sources, oil refineries also discharge selenium to the Bay-Delta, although those discharges have declined in recent years. To understand the effects of changing selenium inputs, scientists have developed the Bay-Delta Selenium Model.



The Bay-Delta Selenium Model is a systematic linked approach for conducting forecasts of selenium (Se) effects on aquatic food webs including higher trophic level animals such as birds and fish (Luoma and Presser, 2000). The methodology is presented as a new tool to predict ecological effects based on the major processes leading from loading through consumer organisms to predators. The approach is illustrated here and can be used with any set of explicitly stated conditions. Forecasts obtained from the Bay-Delta Selenium Model consider (1) loads, (2) water column concentrations, (3) speciation, (4) transformation to particulate forms, (5) particulate concentrations, (6) bioaccumulation, and (7) trophic transfer to predators, in addition to traditional considerations of water supply and drainage demand.

Major inputs used to determine a composite input load are (1) agricultural drainage via direct discharge to the Bay-Delta; (2) effluents from the North Bay oil refineries; (3) San Joaquin River inflows which include agricultural drainage; and (4) Sacramento River inflows. Historical analyses of drainage needs were used to identify the most likely Se loads that would be carried outside the San Joaquin Valley via a conveyance discharging a constant load and conveyance via the San Joaquin River. Selenium concentrations and forms in the Bay-Delta are forecast, then those concentrations are used to model bioaccumulation in invertebrates, like clams. Transfer from clams to predators is estimated from field data, and Se effects on predators are then forecast from data in the existing literature. Data gathered during the years prior to refinery cleanup helped check the model and provide a baseline for determining site-specific effects.

The Se load delivered to the Bay also depends on the amount of flow from the San Joaquin River that passes through the Delta and the amount recycled south

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through the Delta and Tracy pumping stations. The protocol for linking Se load and Se concentration under assigned hydraulic conditions and time duration is:

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

The projections or outputs of the model are presented by season, where a season is defined as six months of predominantly high river inflows (December through May) or six months of predominantly low river inflows (June through November). Riverine influences also depend upon water year type. In combination with flow seasons, forecasts are made for critically dry years or for wet years. A wide range of agricultural Se input loads is possible, depending upon which management strategies are chosen. Potential ranges of annual input loads were derived assuming Se discharge was continuous and are presented here as discharged load per six months (i.e. one-half the annual load under a constant rate of loading).

The model allows consideration of many different drainage options (Luoma and Presser, 2000). In general, most options that meet existing demand for drainage appear to pose strong risks to the reproduction and survival of sensitive birds and fish. Threats to reproduction and survival of birds and fish are particularly severe during periods of low river flow. Vulnerable species include diving ducks, white sturgeon and Sacramento splittail.

Example Selenium Forecast for the San Francisco Bay-Delta

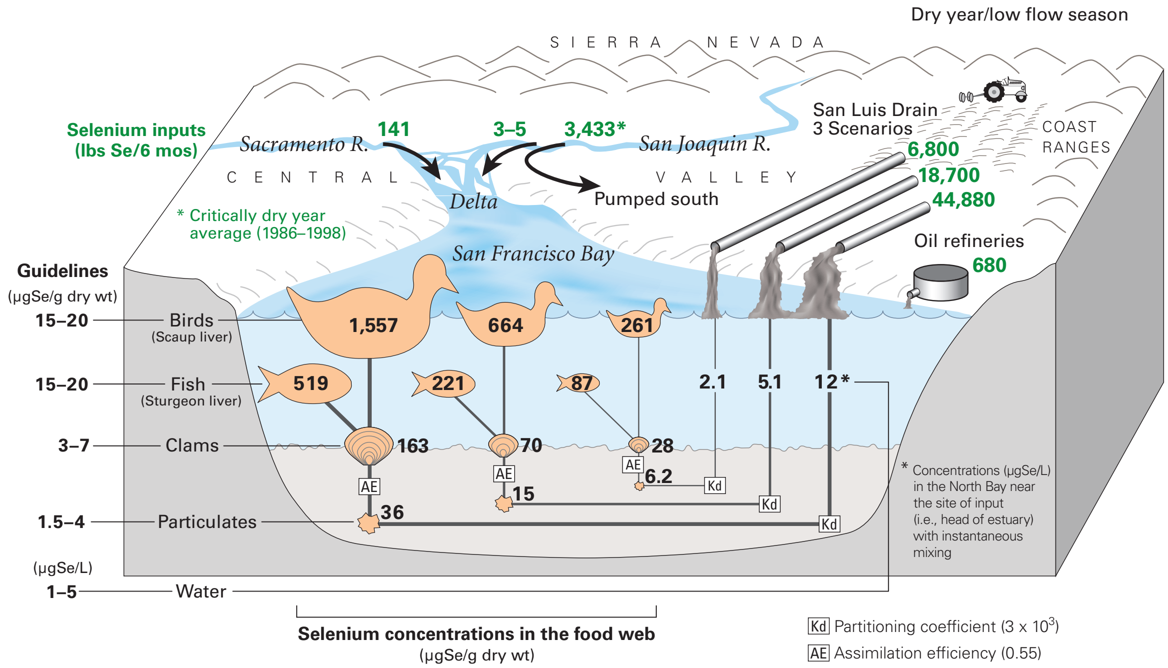
An example forecast is shown (opposite page) for a dry year during the low flow season and with conveyance through a San Luis Drain extension directly to the Bay-Delta. The dry years and low flow seasons will be the ecological bottleneck (the times that will drive impacts) with regard to Se. Surf scoter, greater and lesser scaup, and white sturgeon are present 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 vulnerable.

The example forecast shows Se concentrations for each media forecast (water, particulate, invertebrate, predator), along with guidelines or concentrations where biotic effects are expected (Luoma and Presser, 2000). The forecasts show conditions at the head of the estuary for a range of inputs (6,800; 18,700; or 44,880 pounds Se released per six months) from the San Luis Drain and for a small amount of San Joaquin River inflow to the Bay. The input from oil refineries is assumed constant at 680 pounds Se per six months. We assume a partitioning coefficient (Kd) of 3×10^3 typical of Bay-Delta shallow sediment conditions and a generic bivalve assimilation efficiency (AE) of 0.55 to reflect particulate transformation and bioaccumulation potential from a sediment with a mixture of forms.

In general, the lowest guideline values for waterborne, particulate, dietary, and predator tissue Se are exceeded in every forecast considered in the figure where the input is from a proposed San Luis Drain extension. The highest guidelines from the literature are exceeded in all forecasts except that for the lowest load considered (6,800 pounds per six months) where exceedance does occur for particulates, white sturgeon, and greater and lesser scaup liver. If a San Luis Drain extension is constructed and if it discharges the quantities of Se predicted in our simulation scenarios, during low flow seasons, a high hazard seems likely, with threats to fish and bird species under the load scenarios tested here.

Forecast simulations also were conducted for loading via the San Joaquin River (Luoma and Presser, 2000). If careful management of an out-of-valley resolution to the drainage problem results in discharges of Se via the San Joaquin River to the Bay-Delta (for example at 3,500 pounds per six months), the risks are less than those forecast for a San Luis Drain extension. Under the low flow season of a dry year scenario, the Se concentrations forecast in prey and predators are similar to Se concentrations observed during conditions in the Bay-Delta prior to refinery cleanup. Selenium contamination documented from 1986 to 1996 was sufficient to threaten reproduction in key species within the Bay-Delta estuary ecosystems and resulted in human health advisories being posted for consumption of those species.

The San Luis Drain transports selenium-laden agricltural drainage from the western San Joaquin Valley. Agricultural drainage waterways are posted with a state fish and waterfowl consumption advisory because of selenium.



The Bay-Delta is probably best suited for site-specific Se guidelines and the Bay-Delta Selenium Model could provide a framework for developing new protective criteria. If water quality criteria are to be employed in managing Se inputs, then consideration should be given to the elevated Se concentrations currently occurring in clams and fish of the Bay-Delta, even though waterborne Se concentrations in the Bay-Delta are less than recommended criteria (Luoma and Presser, 2000).

Monitoring Recommendations

A long-term monitoring program is crucial to understanding the fate and impact of management changes for protection of ecosystems receiving Se discharges. Monitoring, as conceptualized below, would sample critical environmental components at a frequency relevant to each process to determine trends in Se contamination or changes in processes that determine fate and effects of Se (Luoma and Presser, 2000).

A linked or combined approach would include all considerations that cause systems to respond differently to Se contamination.

• In any site-specific analysis of Se 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 Se (i.e., agricultural drainage from the San Joaquin Valley via either a dedicated drain or the San Joaquin River).

• The vulnerability of downstream water bodies should be considered when evaluating 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 Se effects (especially if selenate dominates inputs) than adjacent wetlands, the Delta or the Bay, where residence times and biogeochemical transformations of selenate are more likely.

• Any analysis of Se effects must take into account the influences of variable river inflows. Selenium impacts in the Bay-Delta could increase if water diversions increase or if San Joaquin River inflows increase with concomitant increases in Se loading (i.e. the Se 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.

• Establishing a mass balance or budget of Se through the estuary is crucial because internal (oil refinery) and external (agricultural drainage) sources of Se are changing as a result of management. At a minimum, a mechanism for tracking Se 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 on-going 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.

• Storms and high-flow years will be times of increased regional discharge of San Joaquin Valley drainage containing high concentrations and loads of Se. Simulations predict if the precipitation-dependence of agricultural Se 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.

• 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 Se and suspended

Se; Se speciation in water and sediment; assimilation capacities of indicator food chain organisms; and Se concentrations in tissues of prey and predator species.

• Determination of transformation efficiency and processes that determine Kds (distribution or partitioning coefficients) of Se 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.

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

• Determination of food web interrelations would help identify the most vulnerable species. Specific protocols that include life cycles of vulnerable predators including migratory and mobile species would then document Se effects for the species most threatened.

• 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 Se, 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 Se and consideration of 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:

1. Identification of vulnerable food webs
2. Identification of sites most at risk from impacts of agricultural drainage
3. Analysis of effects on predators that includes food web components
4. Identification of elevated risk periods for effects based on hydrodynamics
5. Calculation of protective loads/concentrations based on bioaccumulation in prey

• In view of the analysis of the existing Se 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 may help determine if treating discharge on an annual basis will suffice to manage the current regional imbalance of water, salt, and Se.

• Treatment may also 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 Se in the influent, but result in enhanced Se food chain concentrations if speciation in the effluent changes to increase the efficiency of uptake.

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1. U.S. Environmental Protection Agency (Region 9, Water Division)
2. Contra Costa County
3. Contra Costa Water District

Reference and for additional information:

Forecasting Selenium Discharges to the San Francisco Bay-Delta Estuary: Ecological Effects of A Proposed San Luis Drain Extension, by Samuel N. Luoma and Theresa S. Presser, U.S. Geological Survey Open-File Report 00-416.
http://water.usgs.gov/pubs/ofr00-416/

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Summary of Selenium Issues in California

- Accurate forecasting of the environmental fate of selenium (Se) in the San Francisco Bay-Delta Estuary is crucial because of the element's effect on reproduction in aquatic birds and fish.
- Internal and external sources of Se to the estuary are changing due to water management changes related to the restoration of the San Joaquin River and Bay-Delta.
- Current projects allow discharge to the estuary of saline subsurface waters from the western San Joaquin Valley via the San Joaquin River. Direct conveyance of agricultural drainage to the estuary could occur if an extension of the San Luis Drain is built and discharge permits approved.
- The U.S. Environmental Protection Agency is re-evaluating Se standards for the protection of fish and wildlife. The U.S. Fish and Wildlife Service and the National Marine Fisheries Service through the California Toxics Rule are asking for more stringent Se criteria.
- Selenium concentrations were less than water quality guidelines in both the Delta and the Bay in the latest surveys in 1996. Nevertheless, Se in the food web was sufficient to be a threat to some species and a concern to human health if those species were consumed.