

APPENDIX A: Ecosystem-Scale Selenium Model for the San Francisco Bay-Delta Regional Ecosystem Restoration Implementation Plan (DRERIP)

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A.1—SELENIUM SOURCE DETAIL: REGULATED LOADS AND OTHER INPUTS

Five oil refineries process seleniferous crude oil and discharge selenium (Se) to the North Bay (submodel A, Figure 2). Organic-rich marine basins are the primary source of elevated concentrations of Se in crude oils (Presser and others 2004). Regulation of Se for oil refiners is occurring through water quality Se criteria promulgated by the USEPA for the Bay-Delta (USEPA 1992, 2000a) and limits on effluent loads and concentrations enacted by the State in 1992 (SFBRWQCB 1992a, 1992b, 1993). Compliance with permit limits was achieved in 1998, reducing Se loads from those measured during 1986 to 1992 (Cutter 1989; Cutter and Cutter 2004; Presser and Luoma 2010a). An iterative mass emissions strategy was used *in lieu* of site-specific water quality objectives because water-column Se concentrations were considered not predictive of Se bioaccumulation (SFBRWQCB 1993). A zone of dilution that enables discharge of concentrated Se effluent (34 to 50 $\mu\text{g L}^{-1}$) directly into the bay is allowed as a part of water quality regulations.

Additional North Bay sources of Se under regulatory guidance are the agricultural drains and tributaries that discharge from the west into the Yolo Bypass upstream of tidal influences in the Sacramento River (Larry Walker Associates 2005; Presser and Luoma 2006). Comprehensive monitoring would be necessary to establish (1) when these Se inputs influence the Sacramento River system and the North Delta; and (2) how they are affected by the geologic Se sources of the northern California Coast Ranges, the groundwater hydrology of the area, and the water management practices for the cities of Davis and Woodland, including wetland disposal and treatment (Presser and others 1990; Larry Walker Associates 2005).

Privately owned wastewater treatment plants and industries other than refineries also discharge to the North Bay (SWRCB 2012). Improved data collection would be needed to adequately quantify these Se inputs, but in comparison to permitted oil refinery Se effluents, they are considered secondary (Cutter and San Diego-McGlone 1990; SWRCB 2012). Other potential North Bay sources to consider and monitor with sufficient flow and Se concentration data for accurate Se load calculations are watershed streams that mainly flow to the bay under wet conditions. These streams, however, are not known to be influenced by documented Se sources or conditions of Se enrichment.

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A regulated source of Se from the south is the San Joaquin River. The river receives discharge of seleniferous agricultural drainage from approximately 100,000 acres of farmland in the Grassland Drainage Area of the western San Joaquin Valley (USBR 1995, 2001, 2009a, 2009b; Presser and Luoma 2006; USFWS 2009) (submodel A, [Figure 2](#)). These drainage waters are affected by Se sources in the California Coast Ranges; and, in addition, the arid climate and poor drainage of the southern region intensifies Se accumulation (Presser and Luoma 2006). The riverine and south Delta receiving-water habitats (e.g., backwaters, Stockton Deep Water Ship Channel) are diverse hydrologic environments in terms of Se inputs, Se recycling, and flow (Presser and Luoma 2006). Additionally, the San Joaquin River is undergoing restoration with the goal of increasing flows in the upper reaches to re-establish salmon runs (USBR 2007a). The Delta–Mendota Canal, which carries water south from the Delta, also contains discharge from seleniferous agricultural drains and the San Joaquin River, because a portion of the river is recycled back to the San Joaquin Valley (Presser and Luoma 2006; USFWS 2009; USBR 2011) (submodel A, [Figure 2](#)).

Regulation of Se inputs to the San Joaquin River is implemented through the Grassland Bypass Project (SJVDP 1990; USBR 1995; SFEI 1996–2013). An original agreement signed in 1996 allowed use of a portion of the existing San Luis Drain, the San Joaquin River, and one of its tributaries (Mud Slough) for discharge of agricultural drainage from the Grassland Drainage Area. This agreement has been re-negotiated twice and allows waterways to remain out of compliance with Se water quality criteria until 2019 (USBR 1995, 2001, 2009a, 2009b).

Compliance with regulatory targets has gradually reduced the load of Se discharged into the San Joaquin River (SFEI 2012), although the exact load targets vary with water–year type (CDWR 2010). The ultimate regulatory target is zero discharge to the San Joaquin River. Water conservation, source control, agricultural land retirement, drainage recycling, and drainage reuse on salt tolerant crops all contribute to the reduced Se discharge to the river. As a result of these efforts in 2009, approximately 89% of the Se

in agricultural drainage from the Grasslands Bypass Project was stored in-valley (SFEI 2012). Mitigation measures for this project reduce exposure and attractiveness of habitat to wildlife, and include a flooding contingency plan, monitoring, and provision of 50 acres of rice fields for migratory bird mitigation. The waste treatment lands and management systems are integrated within terrestrial and wetland habitats of the valley, a practice that poses some continuing risks to wildlife, particularly migrating and nesting birds (Presser and Schwarzbach 2008).

The sustainability of these local controls in a limited area of the western San Joaquin Valley is not yet clear. Their management requires considerable effort, cost, and storage capacity within groundwater aquifers, soils, and other mass balance compartments. Nor is it clear that it is feasible to expand on a regional scale the formulated in-valley drainage strategies (e.g., reverse osmosis; enhanced evaporation; Se biotreatment; and surface waste disposal ponds and dumps) and the associated drainage collection and waste-stream facilities (Schoups and others 2005; Presser and Schwarzbach 2008; USBR 2006, 2007b, 2008, 2010). Regional drainage plans and proposals address management in both the 100,000 acres of the Grassland Drainage Area and the adjacent 600,000 acres of the Westlands Water District (USBR 2006, 2007b). Westlands Water District has not been allowed to discharge Se to surface waterways since 1986, an action that exacerbates the effects of the substantial reservoir of Se and salt already stored within the soils and aquifers of that region (Presser and Luoma 2006). Population level effects to aquatic resources (including waterfowl) from Se are predicted both under today's conditions in the western valley (i.e., the proposed no-action alternative) and under proposed in-valley alternatives for provision of drainage service to these areas (USBR 2006, 2007b). Wetland mitigation acreage would be necessary to compensate for avian mortality from drainage reuse and disposal.

In general, progress has been made through regulatory efforts to control Se in-valley and to reduce its transport to the Bay–Delta. But understanding the links between Delta water supply and valley drainage reduction is key to the success of any potential

agricultural Se solution as remedies and restoration move forward both in the western San Joaquin Valley and in the Bay-Delta (Presser and Luoma 2006; California State Senate 2009; Presser and others 2009). The potential for release of Se within the Bay-Delta watershed continues to drive trade-offs such as those among agricultural productivity, degradation of groundwater aquifers, export via the San Joaquin River, and Se exposure of fish and wildlife. For example, infrastructure changes in the Delta could allow more water to be exported to the western San Joaquin Valley, and more San Joaquin River water to enter the Bay. However, implementation of a drainage solution could decrease the amount of water exported to western San Joaquin Valley farms, in an effort to be consistent with proposed drainage reduction and land retirement strategies. Changes also are pending through national legislation (e.g., U.S. House of Representatives 2012) to amounts of water dedicated for environmental purposes (e.g., San Joaquin River restoration), to protections for threatened and endangered species, and to California's system of water rights and transfers. Hence, risks from Se should also be a consideration in future actions proposed for water supply, water delivery, and drainage management within the Bay-Delta watershed.

A.2—EXPOSURE: FOOD WEBS, SEASONAL CYCLES, AND HABITAT USE

DRERIP modeling considers specifics for the following predator species.

Diving Ducks

Species of diving ducks that overwinter in the estuary from September through April include surf scoter, black scoter, greater scaup, and lesser scaup. White-winged scoter are infrequent visitors to the Bay (submodel D, Figure 5). Scaup can make up approximately 50% of total waterfowl in the Bay and up to 92% of migrating Pacific Flyway scaup populations may be in the Bay at one time (Poulton and others 2002). Prey preference in diving ducks helps differentiate Se risk in that scoter and scaup consume *C. amurensis*, while, for example, canvasback prefer *Macoma balthica*. Surf scoters move throughout the Northern Reach during overwintering as prey availability

changes; thus, they can be exposed to different clam species (i.e., *C. amurensis* in the North Bay and *V. philippinarum* in the Central Bay) (De La Cruz and others 2008; De La Cruz 2010). Pacific Coast diving ducks move north in the spring to breeding grounds in Alaska and Canada (De La Cruz and others 2009) (submodel D, Figure 5).

Clapper Rail

The endangered California clapper rail inhabits and breeds in salt marshes that surround the Bay-Delta, mainly in tidal inundation zones. Individuals have a small annual home range and a smaller breeding range, and their movement depends on tidal cycles (Takekawa and others 2011).

Sturgeon

In general, sturgeon are very long-lived (50 to 100 years). White sturgeon migrate upstream to spawn, but they are described as semi-anadromous because they spend a substantial amount of their life in the estuary, especially the North Bay (USFWS 2008a) (submodel D, Figure 5). The endangered green sturgeon is more marine than white sturgeon, spending limited time in the estuary (NOAA Fisheries 2006; Israel and others 2008a; Israel and Kimley 2008b).

Sacramento Splittail

This species, except when they are spawning, are largely confined to the Delta, Suisun Bay, Suisun Marsh, the lower Napa River, and the lower Petaluma River (i.e., 0 to 18 psu) (Kratville 2008). Thus, chronic exposure to estuary contaminants is a concern. Sacramento splittail spawn both in the upper Delta and the estuary (submodel D, Figure 5). Large-scale spawning occurs only in years when watershed floodplains are significantly inundated.

Salmonids

Migratory salmon and trout use the Delta during migration upstream and emigration to the ocean (submodel D, Figure 5). Juvenile Chinook salmon may spend from 3 months to 2 years in freshwater after emergence and before migrating to estuarine areas as smolts, and then into the ocean to feed and mature. Steelhead trout may be best described as nearly year-around spawners (i.e., juveniles may hold

over for many months to a year and may not emigrate to the ocean at all) (USFWS 2008a). Emigrating Central Valley steelhead use the lower reaches of the Sacramento River and the Delta, including tidal marsh areas, non-tidal freshwater marshes, and other shallow water areas, for rearing.

Delta Smelt

This species is of concern to any contaminant because (1) they spent their 1-year life span in the Delta, or close to it, thus being chronically exposed; (2) in any month, two or more life stages can be present in Suisun Bay; and (3) dramatic declines in population threaten extinction (USFWS 2008a).

A.3—FISH AND WILDLIFE HEALTH: ECOTOXICOLOGY AND EFFECTS

DRERIP modeling considers details of Se-specific toxicological information for the following predator species.

Scaup and Scoter

These species consume sub-tidal clams voraciously from their arrival in October to their departure in April as they stage for migration. This pattern puts them at risk from Se effects that influence many facets of their migratory and breeding behavior (sub-models E and F, [Figures 6 and 7](#)). Liver Se concentrations in surf scoter and greater scaup increase as they stage for migration in the Bay (Ohlendorf 1989; Takekawa and others 2002; De La Cruz and others 2008; De La Cruz 2010), as has been found in other overwintering locations (Petrie and others 2007). Studies of waterfowl relate liver Se concentrations to impaired body condition as measured by total protein content (Takekawa and others 2002); stress hormone (corticosterone) levels (Wyland and others 2003); oxidative stress enzyme activity (Hoffman and others 1998, 2002); liver lesions (Heinz and Fitzgerald 1993a, 1993b); and alopecia, and beak and nail necrosis (O'Toole and Raisbeck 1998). Diminished immune system function was associated with a liver Se concentration of $5 \mu\text{g g}^{-1}$ wet weight (or approximately $18.5 \mu\text{g g}^{-1}$ dw) in adult mallards (Hoffman

2002). Poor body condition, in turn, has been linked to decreased winter survival (Haramis and others 1986; Hohman 1993) and also can lead to delayed migration (Drent and others 2006). Delayed migration is linked to missed key prey events along migratory routes (i.e. herring spawns); delayed breeding that results in decreased nesting success; or missed breeding opportunities in boreal forest and arctic nesting species (Drent and others 2006). Breeding propensity in many waterfowl species is dependent on females attaining fat and protein thresholds before migrating (Alisauskas and Ankney 1992; Gorman 2005).

Scaup and scoter migrating from the Bay must arrive in arctic or boreal regions in good condition to initiate nesting, and to have a high likelihood to breed (Alisauskas and Ankney 1992; Esler and others 2001). Species differences affect migration and breeding (De La Cruz and others 2009). For example, spring migration of scaup is the most protracted of all North American ducks, with late nesting also a factor (21 to 56 days from arrival to nest initiation) (Fox and others 2005). In terms of maternal transfer of Se to eggs and effects to offspring themselves, laboratory studies of mallard and lesser scaup eggs showed the potential for depuration of Se during migration to breeding grounds (Heinz 1993; Heinz and Fitzgerald 1993a, b; DeVink and others 2008a; USFWS 2008a; Badzinski and others 2009). Studies of female white-winged scoter at breeding grounds in the Northern Territories showed the persistence of an overwintering liver Se signal, but no relationship between liver Se and egg follicle Se (DeVink and others 2008b, c). Thus, the potential in this species for reproductive fitness effects from Se exposure in staging areas may remain in breeding grounds, but egg Se may represent the Se exposure at the breeding grounds. Studies of lesser scaup (Fox and others 2005; DeVink and others 2008c) argue that egg hatchability and female health effects from Se are not a concern in breeding grounds. The authors note that sampling sizes were small, sampling locations were limited, birds collected were breeding survivors, and studies did not include tracking birds nor measuring Se diet to directly connect Se exposure in staging areas to effects in breeding areas.

Clapper Rail

Concern, in general, is for aquatic-dependent breeding birds that are toxicologically sensitive to Se. Bay-Delta clapper rails show reproductive effects from a combination of contaminants, with mercury being the most prevalent (Lonzarich and others 1992; Schwarzbach and others 2006). As noted previously, diet composition (i.e., which species of clam, mussel, or crab is consumed) and whether prey species are efficient bioaccumulators of Se also are important drivers of Se exposure. The same factors would be of concern for other Se-sensitive breeding birds that are residents (e.g., stilts) (Ackerman and Eagles-Smith 2009).

White Sturgeon

Females reproduce repeatedly over their long lifespan, and have a 2-year internal egg maturation that is conducive to potential Se loading of eggs (Linville 2006) (submodels E and F, [Figures 6 and 7](#)). Each reproductive cycle includes at least 2-years of yolk deposition in the eggs. During this time, accumulated Se is efficiently transferred from the female liver to the yolk of her eggs in a dose-responsive manner (Kroll and Doroshov 1991; Linares and others 2004; Linville 2006). After fertilization and hatching, the developing larvae metabolize over 80% of the stored yolk within a 10-day period. This rapid exposure of Se to the developing larvae can lead to severe development defects (Linville 2006).

Unlike bird species where deformed chicks are outward evidence of Se toxicity, adult fish can survive and appear healthy despite the fact that extensive reproductive failure (i.e., limited survival of deformed larvae) is occurring. In habitats with a history of Se contamination, the possibility exists that the absence or decline of a potentially vulnerable species is attributable to Se. Reproductive and developmental disruption can be detected in the measurement of species recruitment (e.g., “young of the year”). However, in the case of sturgeon, monitoring is typically accomplished by tracking sub-adults and adults, which are generally at least 9 years old (Schaffter and Kohlhorst 1999). Thus, poor recruitment is usually not detected until a decade or more after the hatching of the affected year-class. Additionally, sturgeon exhibit

delayed sexual maturity, with males typically maturing at age 10 to 12 years and females at 15 to 32 years (Doroshov 1985; Doroshov and others 1997). If recruitment dips to levels insufficient to eventually replace the reproductive adults removed through fishing and mortality, the population size will decrease. If reduced recruitment is prolonged, the population can become jeopardized because any managed recovery in recruitment will not affect the population until those year classes become reproductively mature (15 to 32 years for females).

Several studies researched dietary Se exposure specific to effects in white sturgeon (Linares and others 2004; Linville 2006; Tashjian and others 2006). Analysis of data for Se exposure in white sturgeon is given in USFWS (2008a, 2008b).

Sacramento Splittail

Adult splittail feed on bivalves in the North Bay (Stewart and others 2004). Exposure specifically to Se was investigated in several laboratory studies of splittail (Teh and others 2004; Deng and others 2007; Rigby and others 2010).

Chinook Salmon and Steelhead Trout

Concern is for sensitive life stages, and for females during egg development and maternal transport of Se (USFWS 2008a, 2008b) (submodel E, [Figure 6](#)). Species sensitivity distributions of fish species based on either an alevin mortality or larval deformity endpoint show some species of salmonids are more toxicologically sensitive (EC10 egg- or ovary-based) when compared to other species of fish (Janz 2012). Hamilton and others (1990) conducted exposure studies specific to Chinook salmon. As noted previously, no recent or comprehensive study of Se concentrations in Chinook salmon and steelhead trout from the estuary and migration corridors are available.

A.4—DETERMINATION OF HUMAN HEALTH GUIDELINES AND LINKS TO WILDLIFE AND FISH HEALTH

Selenium is an essential micronutrient in animals (Stadtman 1974). Beneficial effects in humans stem mainly from the role of Se as an antioxidant. In the U.S., the national average daily dietary intake exceeds

the nutritional requirements for Se (USDHHS 2002; Institute of Medicine 2000; see also submodel G, Figure 8). However, Se also is the most toxic of all biologically essential elements in mammals, with a very narrow window between what is beneficial and what is toxic (Venugopal and Luckey 1978). Selenium is a target analyte for fish sampling programs to protect human health, with regulation based on systemic selenosis (USEPA 2000b). Fish advisory Se science and, hence, current fish advisories, do not consider possible reproductive effects that occur at lower exposures than direct poisoning of juvenile and adult humans (USDOI 1998). Fish consumption advisories illustrated here are given in dry weight (dw) to facilitate comparison to fish health values.

The USEPA issued revised fish Se advisories in 2000. In 2008, Se guidance was issued for tissue levels and screening values for California sport fish (USEPA 2000b; OEHHA 2008). National and state advisories restrict consumption of fish based upon the Se concentration in the fish, the body weight of the consumer, and the rate of consumption (e.g., grams per day) compared to a reference dose (RfD) (submodel G, Figure 8). Assimilation efficiency is assumed to be 100%. The USEPA defines the RfD as an estimate of a daily oral exposure for the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime (with uncertainty spanning perhaps an order of magnitude). It's derivation includes use of uncertainty factors generally applied to reflect limitations of the data used. Hence, at a specified body weight, each combination of Se concentration in food and consumption rate is converted to, essentially, an uptake rate that can be compared to the recommended RfD. Pregnant women, children, and subsistence fisher populations are examples of sensitive groups for development of specific guidelines. In addition, adjustments can be made for background dietary intakes, as was done recently in the development of fish advisory limits for mercury (USEPA 1997).

Illustrated here, as examples, are limits for Se concentrations in fish as derived for a 70-kg adult consuming meals of 227 g (or 8 ounces) of fish (submodel G, Figure 8). If one 8-ounce meal provides a daily adult RfD of 350 μg Se, then, theoretically, 30 meals

may be eaten per month. However, USEPA (2000b) in general suggests that people eat not more than 16 fish meals per month. Both USEPA (2000b) and the OEHHA (2008) use a Se RfD of 5 μg per kg body weight, per day for calculation of fish advisory tissue Se concentrations (submodel G, Figure 8). From this ingestion rate, the USEPA (2000b) sets a 6.3 $\mu\text{g g}^{-1}$ dw in fish (1.5 $\mu\text{g g}^{-1}$ wet weight; 76% moisture assumed) Se health endpoint for unrestricted consumption (i.e., <16 eight-ounce meals per month). The OEHHA (2008) sets an advisory fish tissue level of 10.4 $\mu\text{g g}^{-1}$ dw in fish (2.5 $\mu\text{g g}^{-1}$ wet weight, 76% moisture assumed) at a consumption rate of three 8-ounce servings per week. This state-derived limit takes into account the mean daily dietary intake of Se as a background consumption rate. The OEHHA (2008) also recommends a fish contaminant goal (i.e., a Se concentration with no significant risk to the average consumer eating 32 g d^{-1}) of 31 $\mu\text{g g}^{-1}$ dw (7.4 $\mu\text{g g}^{-1}$ wet weight, 76% moisture assumed).

Submodel G for Human Health (Figure 8) graphically illustrates derived limits for Se concentrations in fish tissue (dry weight basis) for various combinations of ingestion rate and target dose (i.e., exposure). This graph enables comprehensive translation of specific local, state, or national guidance (e.g., at national per capita, Bay fisher, or national recreational fisher consumption rates) to advisory Se concentrations in tissue. Derivations also can apply to (1) fisher groups (Native American or subsistence) that consume more than an average consumer or (2) sensitive individuals that may require limiting consumption. We broaden the approach used here from the traditional use of $C_{\text{sport fish}}$ in fish advisories to C_{food} to provide a conceptual and quantitative connection to the universality and importance of dietary pathways of Se in determining risk for a range of consumers. For example, derivation of advisory Se concentrations could be applied to wildlife species to expand interconnection and consistency in modeling (Presser and Luoma 2010b). A wildlife criterion (expressed as allowable C_{food}) for use in modeling of consumption of fish by birds, for example, also could be calculated using a species-specific RfD (Presser and Luoma 2010b). In regulatory terminology, a wildlife

criterion is analogous to a tissue residue concentration for human health. Validation would be important; uncertainties in the relationship of body weight and ingestion rate, for example, would need to be considered, but the approach might be helpful in assessing a watershed in terms of avian species. A list of species could be developed, wildlife criteria calculated, and species-specific dietary guidelines applied in modeling (USFWS 2003). Attention to comparable units and conversion factors to account for percent moisture would be necessary for these types of applications (Presser and Luoma 2010b).

Shown in submodel G (Figure 8) are hypothetical calculations, but realistic, scenarios based on consumption with and without adjustment for additional dietary intakes. Sets of fish Se concentration limits are derived for (1) the base scenario of consumption through fishing; (2) a scenario that takes into account a probable daily Se intake based on an estimation of Se in the U.S. diet; and (3) a scenario in which Se supplementation is considered in addition to current dietary intake. In the latter two scenarios, in essence, the target dose is adjusted downward and the derived fish advisory Se concentration limit is reduced from the base scenario (submodel G, Figure 8).

Examples of human health advisory Se concentrations in fish shown in submodel G (Figure 8) help illustrate a connection to fish health. A re-evaluation of the state-of-science for water-quality criteria development by USEPA called for consistency in developing protective Se guidelines to protect wildlife, aquatic species, and humans (Reiley and others 2003). For example, from the scenarios illustrated here, if $5 \mu\text{g g}^{-1} \text{ dw}$ is considered protective of fish health, then USEPA's fish advisory Se concentrations designated to protect adult human health exceed that value, making fish health the driving factor (submodel G, Figure 8). The values to protect fish and human health are comparable when considering an adult intake of $350 \mu\text{g d}^{-1}$ (target dose of $350 \mu\text{g}$ per 70-kg adult, per day) at increased fish consumption (i.e., $>200 \text{ g d}^{-1}$) or an adult intake of 236 or $175 \mu\text{g d}^{-1}$ (target dose of 236 or $175 \mu\text{g}$ per 70-kg adult, per day) at increased fish consumption (i.e., 150 g d^{-1}).

REFERENCES

- Ackerman JT, Eagles-Smith CA. 2009. Selenium bioaccumulation and body condition in shorebirds and terns breeding in San Francisco Bay, California, USA. *Environmental Toxicology and Chemistry* 28(10):2134–2141.
- Alisauskas RT, Ankney CD. 1992. The cost of egg laying and its relationship to nutrient reserves in waterfowl. In: Batt BDJ, Afton AD, Anderson MG, Ankney CD, Johnson DH, Kadlec JA, Krapu GL, editors. *Ecology and management of breeding waterfowl*. Minneapolis, (MN): University of Minnesota Press. p 30–61.
- Badzinski SS, Flint PL, Gorman KB, Petrie SA. 2009. Relationships between hepatic trace element concentrations, reproductive status, and body condition of female greater scaup. *Environmental Pollution* 157(6):1886–1893.
- [CDWR] California Department of Water Resources. 2010. Chronological reconstructed Sacramento and San Joaquin Valley water year hydrologic classification indices. Sacramento (CA): California Department of Water Resources. 4 p. Available from: <http://cdec.water.ca.gov/cgi-progs/ioidir/WSIHIST> Accessed 11 June 2012.
- [OEHHA] California Office of Environmental Health Hazard Assessment. 2008. Development of fish contaminant goals and advisory tissue levels for common contaminants in California sport fish: chlordane, DDT's, dieldrin, methylmercury, PCB's, selenium and toxaphene. Sacramento (CA): California Environmental Protection Agency. 115 p. Available from: <http://www.oehha.ca.gov/fish/gtlsx/crn062708.html> Accessed 11 June 2012.
- [SFBRWQCB] California San Francisco Bay Regional Water Quality Control Board. 1992a. Derivation site-specific water-quality criteria for selenium in San Francisco Bay. Oakland (CA): California San Francisco Bay Regional Water Quality Control Board. 37 p.

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- [SFBRWQCB] California San Francisco Bay Regional Water Quality Control Board. 1992b. Mass emissions reduction strategy for selenium. Oakland (CA): California San Francisco Bay Regional Water Quality Control Board. 53 p + 1 appendix.
- [SFBRWQCB] California San Francisco Bay Regional Water Quality Control Board. 1993. Mass emissions reduction strategy for selenium: supplement. Oakland (CA): California San Francisco Bay Regional Water Quality Control Board. 61 p.
- [SWRCB] California State Water Resources Control Board. 2012. Data retrieval, California Integrated Water Quality System, ESMR At-a-glance report criteria. Sacramento (CA): California State Water Resources Control Board. Available from: <http://ciwqs.waterboards.ca.gov/ciwqs/readOnly/PublicReportEsmrAtGlanceServlet?inCommand=reset> Accessed 11 June 2012.
- California State Senate. 2009. Sacramento–San Joaquin Delta Reform Act (SB 12) (California Water Code Section 85300–85309). Sacramento (CA): California State Senate. 39 p.
- Cutter GA. 1989. The estuarine behavior of selenium in San Francisco Bay. *Estuarine, Coastal, and Shelf Science* 28(1):13–34.
- Cutter GA, Cutter LS. 2004. Selenium biogeochemistry in the San Francisco Bay estuary: changes in water column behavior. *Estuarine, Coastal and Shelf Science* 61(3):463–476.
- Cutter GA, San Diego–McGlone MLC. 1990. Temporal variability of selenium fluxes in San Francisco Bay. *Science of the total environment* 97/98:235–250.
- De La Cruz SE. 2010. Habitat, diet, and contaminant relationships of surf scoters wintering in San Francisco Bay: implications for conservation in urban estuaries. [PhD dissertation]. Davis (CA): University of California Davis 215 p.
- De La Cruz SEW, Takekawa JY, Miles A, Eadie JM, Palm EC, Wilson MT. 2008. The influence of winter habitat use and diet on selenium risks for surf scoters (*Melanitta perspicillata*) in the San Francisco Bay Estuary [abstract]. State of the San Francisco Estuary Conference; 22–24 October 2008; Oakland, California. Oakland (CA): The San Francisco Estuary Project. 1 p.
- De La Cruz SEW, Takekawa JY, Wilson MT, Nysewander DR, Evenson JR, Esler D, Boyd WS, Ward DH. 2009. Spring migration routes and chronology of surf scoters (*Melanitta perspicillata*): a synthesis of Pacific coast studies. *Canadian Journal of Zoology* 87(11):1069–1086.
- Deng DF, Hung SS, Teh SJ. 2007. Selenium depuration: residual effects of dietary selenium on Sacramento splittail (*Pogonichthys macrolepidotus*). *Science of the Total Environment* 377(2–3):224–32.
- DeVink J–MA, Clark RG, Slattery SM, Scheuhammer AM. 2008a. Effects of dietary selenium on reproduction and body mass of captive lesser scaup. *Environmental Toxicology and Chemistry* 27(2):471–477.
- DeVink J–MA, Clark RG, Slattery SM, Scheuhammer AM. 2008b. Cross-seasonal association between winter trophic status and breeding ground selenium levels in boreal white-winged scoters. *Avian Conservation and Ecology* 3(1):3.
- DeVink J–MA, Clark RG, Slattery SM, Wayland M. 2008c. Is selenium affecting body condition and reproduction in boreal breeding scaup, scoters, and ring-necked ducks? *Environmental Pollution* 152(1):116–122.
- Doroshov SI. 1985. Biology and culture of sturgeon Acipenseriformes. In: Muir JF, Roberts RJ, editors. *Recent advances in aquaculture*. London (UK): Croom Helm. p. 251–274.
- Doroshov SI, Moberg GP, Van Eenennaam JP. 1997. Observations on the reproductive cycle of cultured white sturgeon, *Acipenser transmontanus*. *Environmental Biology of Fishes* 48(1–4):265–278.
- Drent RH, Fox AD, Stahl J. 2006. Traveling to breed. *Journal of Ornithology* 147:122–134.

- Esler D, Grand JB, Afton AD. 2001. Intraspecific variation in nutrient reserve use during clutch formation in lesser scaup. *The Condor* 104(4): 810–820.
- Fox GA, MacCluskie MC, Brook RW. 2005. Are current contaminant concentrations in eggs and breeding female lesser scaup of concern? *The Condor* 107(1):50–61.
- Gorman KB. 2005. Reproductive energetics of female greater scaup (*Aythya marila*): nutritional and physiological correlates of timing and state of reproduction. [MA thesis]. Burnaby (BC): Simon Fraser University. 115 p.
- Hamilton SJ, Buhl KJ, Faerber NL, Bullard FA, Wiedmeyer RH. 1990. Toxicity of organic selenium in the diet to Chinook salmon. *Environmental Toxicology and Chemistry* 9(3):347–358.
- Haramis GM, Nichols JD, Pollock KH, Hines JE. 1986. The relationship between body mass and survival of wintering canvasbacks. *The Auk* 103(3):506–514.
- Heinz GH. 1993. Selenium accumulation and loss in mallard eggs. *Environmental Toxicology and Chemistry* 12(4):775–778.
- Heinz GH, Fitzgerald MA. 1993a. Reproduction of mallards following overwinter exposure to selenium. *Environmental Pollution* 81(2):117–122.
- Heinz GH, Fitzgerald MA. 1993b. Overwinter survival of mallards fed selenium. *Archives of Environmental Contamination and Toxicology* 25(1):90–94.
- Hoffman DJ. 2002. Role of selenium and oxidative stress in aquatic birds. *Aquatic Toxicology* 57(1–2):11–26.
- Hoffman DJ, Ohlendorf HM, Marn CA, Pendleton GW. 1998. Association of mercury and selenium with altered glutathione metabolism and oxidative stress in diving ducks from the San Francisco Bay region, USA. *Environmental Toxicology and Chemistry* 17(2):167–172.
- Hoffman, DJ, Marn C, Marois K, Sproul E, Dunne M, Skorupa JP. 2002. Sublethal effects in avocet and stilt hatchlings from selenium-contaminated sites. *Environmental Toxicology and Chemistry* 21(3):561–566.
- Hohman WL. 1993. Body composition of wintering canvasbacks in Louisiana: dominance and survival implications. *The Condor* 95(2):377–387.
- Institute of Medicine. 2000. Dietary reference intakes for vitamin C, vitamin E, selenium and carotenoids. Washington (DC): National Academy Press. 506 p.
- Israel J, Drauch A, Gingras M. 2008a. Life history conceptual model for white sturgeon (*Acipenser transmontanus*). Current DRERIP conceptual models. Sacramento (CA): California Department of Fish and Game. 54 p. Available from: http://www.dfg.ca.gov/erp/cm_list.asp Accessed 11 June 2012.
- Israel J, Klimley AP. 2008b. Life history conceptual model for green sturgeon (*Acipenser medirostris*). Current DRERIP conceptual models. Sacramento (CA): California Department of Fish and Game. 49 p. Available from: http://www.dfg.ca.gov/erp/cm_list.asp Accessed 12 June 2012.
- Janz DM. 2012. Selenium. In: Wood CW, Farrell AP, Brauner CJ, editors. *Fish physiology*. Volume 31A: homeostasis and toxicology of essential metals. San Diego (CA): Elsevier. p 327–374.
- Kratville D. 2008. Delta Regional Ecosystem Restoration Implementation Plan (DRERIP) semi-final species life history conceptual model, Sacramento splittail (*Pogonichthys macrolepidotus*). Sacramento (CA): California Department of Fish and Game. 33 p.
- Kroll KJ, Doroshov SI. 1991. Vitellogenin: potential vehicle for selenium bioaccumulation in oocytes of the white sturgeon (*Acipenser transmontanus*). In: Williot P, editor. *Acipenser*: Proceedings of the 1st International Sturgeon Conference; 3–6 October 1989; Bordeaux, France. Bordeaux, France: *Centre National du Machinisme Agricole du Genie Rural des Eaux et des Forets*. p 99–106.

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

- Larry Walker Associates. 2005. Yolo Bypass water quality management plan report. Prepared under CALFED Watershed Grant 4600001691 for the City of Woodland. Davis (CA): Larry Walker Associates. 90 p + 7 appendices.
- Linares J, Linville RG, Van Eenennaam J, Doroshov S. 2004. Selenium effects on health and reproduction of white sturgeon in the Sacramento–San Joaquin Estuary. Final Report, Project No. ERP-02-P35. Davis, (CA): University of California, Department of Animal Science. 56 p.
- Linville RG. 2006. Effects of excess selenium on the health and reproduction of white sturgeon (*Acipenser transmontanus*): implications for San Francisco Bay–Delta. [Phd dissertation]. Davis (CA): University of California Davis. 232 p.
- Lonzarich DG, Harvey TE, Takekawa JE. 1992. Trace elements and organochlorine concentrations in California clapper rail (*Rallus longirostris obsoletus*) eggs. Archives of Environmental Contamination and Toxicology 23(2):147–153.
- [NOAA Fisheries] National Oceanic and Atmospheric Administration, National Marine Fisheries Service. 2006. Threatened status for southern distinct population segment of North American green sturgeon. Federal Register 71(67). Apr 7 2006. 50 CFR Part 223 [No. 050323081-6079-02, RIN 0648-AT02].
- Ohlendorf HM. 1989. Bioaccumulation and effects of selenium in wildlife. In: Jacobs LW, editor. Selenium in agriculture and the environment. Special Publication No. 23. Madison (WI): Soil Science Society of America. p 133–177.
- O'Toole D, Raisback MF. 1998. Magic numbers, elusive lesions: comparative pathology and toxicology of selenosis in waterfowl and mammalian species. In: Frankenberger WT, Engberg RA, editors. Environmental chemistry of selenium. New York (NY): Marcel Dekker. p 355–395
- Petrie S.A, Badzinski SS, Drouillard KG. 2007. Contaminants in lesser and greater scaup staging on the lower Great Lakes. Archives of Environmental Contamination and Toxicology 52(4):580–589.
- Presser TS, Luoma SN. 2006. Forecasting selenium discharges to the San Francisco Bay–Delta Estuary: ecological effects of a proposed San Luis Drain extension. U.S. Geological Survey Professional Paper 1646. 196 p. Available from: <http://pubs.usgs.gov/pp/p1646/> Accessed 12 June 2012.
- Presser TS, Luoma SN. 2010a. Ecosystem-scale modeling in support of fish and wildlife selenium criteria development for the San Francisco Bay–Delta Estuary, California, U.S. Geological Survey Administrative Report prepared for (2010) and released by USEPA (2011), Region 9, San Francisco, California. 101 p + appendices A–D. Available from: <http://www.epa.gov/region9/water/ctr> Accessed 12 June 2012.
- Presser TS, Luoma SN. 2010b. A methodology for ecosystem-scale modeling of selenium. Integrated Environmental Assessment and Management 6(4):685–710.
- Presser TS, Schwarzbach SE. 2008. Technical analysis of in-valley drainage management strategies for the western San Joaquin Valley, California: U.S. Geological Survey Open-File Report 2008-1210. 37 p. Available from: <http://pubs.usgs.gov/of/2008/1210/> Accessed 12 June 2012.
- Presser TS, Swain WC, Tidball RR, Severson RC. 1990. Geologic sources, mobilization, and transport of selenium from the California coast ranges to the western San Joaquin Valley: a reconnaissance study. U.S. Geological Survey Water-Resources Investigations Report 90-4070. 66 p.
- Presser TS, Jenni KE, Nieman T, Coleman JL. 2009. Decision analysis framing study: in-valley drainage management strategies for the western San Joaquin Valley, California. U.S. Geological Survey Open-File Report 2009-1121. 12 p. Available from: <http://pubs.usgs.gov/of/2009/1121/> Accessed 12 June 2012.

Presser TS, Piper DZ, Bird KJ, Skorupa JP, Hamilton SJ, Detwiler SJ, Huebner MA. 2004. The Phosphoria Formation: a model for forecasting global selenium sources to the environment. In: Hein J, editor. Life cycle of the Phosphoria Formation: from deposition to the post-mining environment. New York (NY): Elsevier. p 299–319. Available from: http://www.rcamnl.wr.usgs.gov/Selenium/Library_articles/chap11_global_Se-optimized.pdf Accessed 12 June 2012.

Poulton VK, Lovvorn JR, Takekawa JY. 2002. Clam density and scaup feeding behavior in San Pablo Bay, California. *The Condor* 104(3):518–527.

Reiley MC, Stubblefield WA, Adams WJ, Di Toro DM, Hodson PV, Erickson RJ, Keating FJ Jr, editors. 2003. Reevaluation of the state of the science for water-quality criteria development. Pensacola (FL): SETAC Press. 224 p.

Rigby MC, Deng X, Grieb TM, Teh SJ, Hung SSO. 2010. Effect threshold for selenium toxicity in juvenile splittail, *Pogonichthys macrolepidotus*. *Bulletin of Environmental Contamination and Toxicology* 84(1):76–79.

[SFEI] San Francisco Estuary Institute. 1996–2013. Grassland Bypass project reports. Prepared for the U.S. Bureau of Reclamation. Oakland (CA): San Francisco Estuary Institute. Available from: <http://www.sfei.org/gbp/reports> Accessed 12 June 2012.

[SFEI] San Francisco Estuary Institute. 2012. Grassland Bypass Project 2008–2009 annual report. Prepared for the U.S. Bureau of Reclamation. Oakland (CA): San Francisco Estuary Institute. 284 p. Available from: <http://www.sfei.org/gbp/reports> Accessed 12 June 2012.

[SJVDP] San Joaquin Valley Drainage Program. 1990. A management plan for agricultural subsurface drainage and related problems on the westside San Joaquin Valley. Sacramento (CA): San Joaquin Valley Drainage Program. 183 p.

Schaffter RG, Kohlhorst DW. 1999. Status of white sturgeon in the Sacramento–San Joaquin Estuary. *California Fish and Game* 85(1):37–41.

Schoups G, Hopmans JW, Young CA, Vrugt JA, Wallender WW, Tanji KK. 2005. Sustainability of irrigated agriculture in the San Joaquin Valley, California. *Proceeding of the National Academy of Science* 102(43):15352–15356.

Schwarzbach SE, Albertson JD, Thomas CM. 2006. Impacts of predation, flooding, and contamination on the reproductive success of the California clapper rail (*Rallus longirostris obsoletus*) in San Francisco Bay. *The Auk* 123(1):45–60.

Stadtman TC. 1974. Selenium biochemistry. *Science* 183(4128):915–922.

Stewart AR, Luoma SN, Schlekot CE, Doblin MA, Hieb KA. 2004. Food web pathway determines how selenium affects ecosystems: a San Francisco Bay case study. *Environmental Science and Technology* 38(17):4519–4526.

Takekawa JY, Wainwright–De La Cruz SE, Hothem RL, Yee J. 2002. Relating body condition to inorganic contaminant concentrations of diving ducks wintering in coastal California. *Archives of Environmental Contamination and Toxicology* 42(1):60–70.

Takekawa JY, Woo I, Gardiner R, Casazza M, Ackerman JT, Nur N, Liu L, Spautz H. 2011. Avian communities in tidal salt marshes of San Francisco Bay: a review of functional groups by foraging guild and habitat association. *San Francisco Estuary and Watershed Science* [Internet]. Available from: <http://www.escholarship.org/uc/item/3tg4f18n> Accessed 20 March 2013.

Tashjian DH, Teh SJ, Sogomonyan A, Hung SSO. 2006. Bioaccumulation and chronic toxicity of dietary L-selenomethionine in juvenile white sturgeon (*Acipenser transmontanus*). *Aquatic Toxicology* 79(4):401–409.

Teh SJ, Deng X, Deng DF, Teh FC, Hung SS, Fan TW, Liu J, Higashi RM. 2004. Chronic effects of dietary selenium on juvenile Sacramento splittail (*Pogonichthys macrolepidotus*). *Environmental Science and Technology* 38(22):6085–93.

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

[USBR] U.S. Bureau of Reclamation. 1995. Finding of no significant impact and supplement environmental assessment, Grassland Bypass Channel Project, interim use of a portion of the San Luis Drain for conveyance of drainage water through the Grassland Water District and adjacent Grassland areas. Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region. 36 p + appendices.

[USBR] U.S. Bureau of Reclamation. 2001. Grassland Bypass Project environmental impact statement and environmental impact report. Volume I (main text; appendices A and I) and volume II (appendices B–H). Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region.

[USBR] U.S. Bureau of Reclamation. 2006. San Luis drainage feature re-evaluation environmental impact statement. Executive summary, sections 1–24, appendices A–P. Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region. 2,785 p.

[USBR] U.S. Bureau of Reclamation. 2007a. San Joaquin River Restoration Program Management Plan, implementation of settlement agreement. (U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, National Marine Fisheries Service, California Department of Water Resources, California Department of Fish and Game). Sacramento (CA): U.S. Bureau of Reclamation. 54 p + attachments A–H. Available from: http://www.restoresjr.net/program_library/06-Settlement_Related/index.html Accessed 12 June 2012.

[USBR] U.S. Bureau of Reclamation. 2007b. San Luis drainage feature re-evaluation record of decision. Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region. 41 p.

[USBR] U.S. Bureau of Reclamation. 2008. San Luis drainage feature re-evaluation feasibility report. Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region. 193 p + appendices A–M.

[USBR] U.S. Bureau of Reclamation. 2009a. Grassland Bypass Project 2010–2019 record of decision. Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region. 14 p.

[USBR] U.S. Bureau of Reclamation. 2009b. Grassland Bypass Project (2010–2019) environmental impact statement and environmental impact report. Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region. 391 p + appendices A–H. Available from: http://www.usbr.gov/mp/nepa/documentShow.cfm?Doc_ID=4412 Accessed 12 June 2012.

[USBR] U.S. Bureau of Reclamation. 2010. Letter to Senator Feinstein, U.S. Senate, Washington DC, dated 9/1/2010 from Michael Connor, Commissioner. Washington (DC): U.S. Bureau of Reclamation. 5 p.

[USBR] U.S. Bureau of Reclamation. 2011. Delta–Mendota Canal water quality monitoring report, quarterly report of flows, concentrations and loads of salts and selenium (on-going series). Sacramento (CA): U.S. Bureau of Reclamation Mid-Pacific Region. 39 p.

[USDO] U.S. Department of the Interior. 1998. Guidelines for interpretation of effects of selected constituents in biota, water, and sediment – selenium. 47 p. Available from: <http://www.usbr.gov/niwqp/guidelines/pdf/Selenium.pdf> Accessed 12 June 2012

[USDHHS] U.S. Department of Health and Human Services. 2002. Dietary intake of macronutrients, micronutrients and other dietary constituents. United States 1988–1994. National Center for Health Statistics. Vital Health Statistics 11(245).

[USEPA] U.S. Environmental Protection Agency. 1992. Rulemaking, water quality standards, establishment of numeric criteria for priority toxic pollutants, states' compliance (National Toxics Rule), Final Rule: Federal Register 57(242:60848).

[USEPA] U.S. Environmental Protection Agency. 1997. Mercury study report to Congress, volume VII: characterization of human health and wildlife risks from mercury exposure in the United States. EPA-452/R-97-009. 152 p.

[USEPA] U.S. Environmental Protection Agency. 2000a. Water quality standards: establishment of numeric criteria for priority toxic pollutants for the State of California (California Toxics Rule): Federal Register 65(97):31681–31719. Available from: <http://regulations.vlex.com/vid/environmental-protection-agency-23304844> Accessed 12 July 2012

[USEPA] U.S. Environmental Protection Agency. 2000b. Guidance for assessing chemical contaminant data for use in fish advisories. Volume 2: risk assessment and fish consumption limits. 3rd edition. EPA 823-B-00-008. November 2000. 383 p.

[USFWS] U.S. Fish and Wildlife Service. 2003. Evaluation of the Clean Water Act section 304(a) human health criterion for methylmercury: Protectiveness for threatened and endangered wildlife in California Sacramento (CA): U.S. Fish and Wildlife Service. 112 p. Available from: http://www.fws.gov/sacramento/ec/Investigations-And_Prevention/Home/Documents/Methylmercury%20Criterion%20Evaluation%20Final%20Report%20October%202003.pdf Accessed 16 July 2012.

[USFWS] U.S. Fish and Wildlife Service. 2008a. Species at risk from selenium exposure in the San Francisco estuary. Sacramento (CA): U.S. Fish and Wildlife Service, Sacramento Fish and Wildlife Office. 81 p.

[USFWS] U.S. Fish and Wildlife Service. 2008b. Potential effects of selenium contamination on federally-listed species resulting from delivery of federal water to the San Luis Unit. Sacramento (CA): U.S. Fish and Wildlife Service, Sacramento Fish and Wildlife Office. 46 p.

[USFWS] U.S. Fish and Wildlife Service. 2009. Endangered species consultation on the proposed continuation of the Grassland Bypass Project, 2010–2019. Sacramento (CA): U.S. Fish and Wildlife Service, Sacramento Fish and Wildlife Office. 198 p.

U.S. House of Representatives. 2012. San Joaquin Valley Water Reliability Act, H.R. 1837, U.S. Washington (DC): House of Representatives. 21 p.

Venugopal B, Luckey TD. 1978. Metal toxicity in mammals. Volume 2, chemical toxicity of metals and metalloids. New York (NY): Plenum Press. 409 p.

Wyland M, Smits JEG, Gilchrist HG, Marchant T, Keating J. 2003. Biomarker responses in nesting common eiders in the Canadian Arctic in relation to tissue cadmium, mercury and selenium concentrations. *Ecotoxicology* 12(1–4):225–237.