CONTAMINANTS IN DRAINAGE WATER AND AVIAN RISK THRESHOLDS

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THE ECONOMICS AND MANAGEMENT OF WATER AND DRAINAGE IN AGRICULTURE

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ABSTRACT

The toxicity of selenium to avian embryos is one of the most restrictive constraints on options for managing agricultural drainage water. Although selenium in eggs strongly predicts embryotoxicity, waterborne selenium (on a total recoverable basis) often is an unreliable predictor of average realized selenium in eggs. For the San Joaquin Valley, however, the algebraically derived equation Log (Mean Egg Se) = 3.66 + 0.57 Log (Waterborne Se) is a good predictor of the maximum potential for selenium bioaccumulation in avian eggs. Using eared grebes (Podiceps nigricollis) as an indicator species for bioaccumulation potential, the average absolute difference between observed and predicted mean selenium in eggs was only 6 percent for test cases at waterborne concentrations of 2.8, 15, 126, 176 p/b (total recoverable) selenium. Various estimates of biologically important thresholds indicate that it would be prudent to consider drainage water with 3 to 20 p/b selenium as peripherally hazardous to aquatic birds (i.e., hazardous to some species under some environmental conditions) and drainage water with more than 20 p/b selenium as widely hazardous to aquatic birds (i.e., hazardous to most species under most environmental conditions). To prevent most avian toxicity, a reasonable goal for chemical or biological decontamination technologies would be concentrations of waterborne selenium < 10 p/b. Likewise, to minimize avian contamination, a reasonable goal of purity would be waterborne selenium < 2.3 p/b. When these water standards are technically or financially unattainable, actions to significantly reduce avian use of contaminated drainage water are necessary.

INTRODUCTION

Over the past four decades, many water projects made it possible to irrigate large tracts of otherwise nonarable land in the arid western United States. For example, irrigated croplands increased in the Central Valley of California by 43 percent between 1959 and 1975 (Shelton, 1987). A substantial portion of this land, however, requires artificial drainage of shallow ground water to maintain crop productivity (Letey et al., 1986). In California more than 500 million cubic meters of this subsurface agricultural drainage water (drainage water) are already discharged annually (Ohlendorf and Skorupa, 1989) to surface aquatic ecosystems, primarily the San Joaquin River, its west-side tributaries, the Delta-Mendota Canal, evaporation ponds in the Tulare Basin, or the Salton Sea and its principal tributaries.

Concurrent with agricultural and other development (including pre-1959), more than 90 percent of the Central Valley's historic wetlands have been lost (Moore et al., 1990). Remnant wildlife populations have been concentrated onto the remaining wetlands, including those receiving drainage water. In at least one area, the Tulare Basin of California's southern San Joaquin Valley, ponds for evaporative reduction of drainage water (evaporation ponds) are typically the most common type of wetland available to wildlife during the spring (Moore et al., 1990). The shallow and nutrient-enriched waters of evaporation ponds lead to high primary and secondary productivity (Euliss, 1989) and provide the ready source of proteinaceous foods required by breeding birds. Accordingly, the ponds are particularly attractive to breeding waterbirds (Schroeder et al., 1988) and provide a pathway for wildlife exposure to contaminants in drainage water.

Although environmental exposure to drainage-water contaminants is documented for amphibians, reptiles, birds, and mammals, the impairment of avian reproduction is the most pronounced adverse biological effect documented for wildlife (Ohlendorf and Skorupa, 1989). It is this effect that will most likely impinge on the economics of drainage-water management because, under the Federal Migratory Bird Treaty Act (16 U.S.C. Sections 703-712), migratory birds are legally protected from human-caused poisoning (Olive and Johnson, 1986). The cost of drainage-water treatment, for example, depends on the standard of purity for treated water. The legal mandate that requires management of drainage water to be protective of migratory birds (including their embryos) is apparently the most restrictive constraint on acceptable standards of purity and acceptable methods for disposal of drainage water--treated or untreated. Therefore, this chapter attempts to clarify some of the biological constraints on drainage-water management by focusing principally on aquatic birds and on the toxicity of drainage-water contaminants to avian embryos (i.e., embryotoxicity as indicated by the overt deformity or death of an embryo).

Nearly a dozen inorganic constituents in drainage water are of toxicological concern (CSWRCB, 1987). Many of these constituents are found in tissues of wildlife sampled at evaporation ponds including arsenic, boron, cadmium, mercury, molybdenum, selenium, and strontium (Moore et al., 1989). Selenium, however, is the only constituent commonly found at embryotoxic concentrations in the eggs of aquatic birds (Ohlendorf and Skorupa, 1989). Experimental studies (Heinz et al., 1989 and Hoffman and Heinz, 1988) confirmed that the toxic effects of selenium alone are sufficient to explain most adverse effects on avian reproduction observed at evaporation ponds.

Boron, molybdenum, and strontium also have been detected at elevated levels in bird eggs from evaporation ponds. Elevated concentrations of boron and molybdenum (Ohlendorf and Skorupa, 1989 and Skorupa et al., unpubl. data) are usually well below known thresholds for avian embryotoxicity (Smith and Anders, 1989 and Eisler, 1989). The authors are unaware of critical threshold values for strontium-induced avian embryotoxicity, but eggs with elevated levels of strontium (i.e., > 75 p/m) are rare. (All tissue concentrations of contaminants cited in this chapter are on a dry-weight basis.)

In addition to the individual toxicity of drainage-water contaminants, chemical interactions can result in magnification or reduction of a contaminant's embryotoxicity. Also, noninteractive additive effects can cause cumulative toxicity, even though all the individual contaminants are below embryotoxic thresholds. The potential for interactive embryotoxic effects was evaluated in two experimental studies. Smith and Heinz (1990) found that the embryotoxic effects of boron and selenium seemed to be neither synergistic nor additive. Another study (USFWS,1990) focused on the interaction between selenium and arsenic and found that 400 p/m dietary sodium arsenate reduced the embryotoxicity of 10 p/m dietary selenomethionine. In nature, however, the aquatic invertebrates that constitute the dietary staple of aquatic birds at evaporation ponds (Euliss, 1989) rarely exceed 25 p/m arsenic (Moore et al., 1989). Arsenic was below the limit of detection (ca. 0.4 p/m) in all bird eggs sampled from evaporation ponds (Moore et al., 1989 and Skorupa et al., unpubl. data). Although evaluation of the potential for interactive effects should be continued, current evidence is not compelling for important interactive or additive embryotoxic effects in the field. Therefore, as a matter of parsimony, the contaminant focus of this chapter will be on selenium toxicity.

The objective here, within the overall theme of biological constraints on drainage-water management, is to review and provide new syntheses of the results of field and laboratory studies of selenium embryotoxicity in birds. This chapter will emphasize what is known about significant thresholds and then discuss the general implications for the management of drainage water.

For this chapter, "avian contamination" is defined as mean selenium in eggs (mean egg selenium) above normal (background) concentrations, and "avian toxicity" is defined as mean egg selenium above embryotoxic thresholds. Avian contamination per se warrants the separate consideration given here because so little is known about subtle nonlethal adverse effects of selenium on avian embryos or about secondary hazards to predators of avian eggs.

To maintain a standard of best available information, unpublished data are cited occasionally in this review. When the unpublished data are the authors', the data are presented in appropriate detail. When they are not the authors', the details have been considered (usually from the raw data), but are not presented here. Results from both population-level analyses and individual-level analyses are discussed. It is stressed that these levels of analyses are not interchangeable.

SELENIUM AND THE KESTERSON SYNDROME

Selenium is an essential trace element in animal diets, but the range between nutritional requirements and toxic levels is narrow (Ganther, 1974). In areas with seleniferous soils, selenium toxicosis was documented in poultry and livestock more than 50 years ago (e.g., Poley et al., 1937). Few studies, however, were conducted before the 1980's to examine selenium toxicity in wildlife (Ohlendorf, 1989).

Toxicity in wildlife was first observed at Kesterson Reservoir (Kesterson), a drainage-water evaporation pond system in the northern San Joaquin Valley. Field and controlled experimental studies identified selenium as the principal cause of embryotoxicity among birds at Kesterson (Ohlendorf, 1989). The drainage water discharged to Kesterson Reservoir during 1983-85 averaged about 300 p/b selenium (Presser and Barnes, 1984 and Saiki and Lowe, 1987). This extremely high concentration of selenium in the water (concentrations are normally < 1 p/b; e.g., Schroeder et al., 1988) was bioaccumulated to levels in avian foods, such as aquatic plants and insects, that were typically more than 30 times the normal concentrations for these taxa (Ohlendorf, 1989).

The extreme conditions at Kesterson provided little opportunity to assess thresholds for selenium toxicity to aquatic birds (but see Ohlendorf et al., 1986). However, two major research schemes, one directed by the U.S. Department of Interior National Irrigation Water Quality Program (Sylvester et al., 1989) and one directed by the U.S. Fish and Wildlife Service Patuxent Wildlife Research Center (USFWS, 1990), have recently expanded the basis for understanding avian exposure to selenium and the thresholds for toxicity.

REFERENCE VALUES FOR SELENIUM IN EGGS OF WILD BIRDS

As of the early 1980's when Eisler (1985) reviewed selenium hazards to fish, wildlife, and invertebrates, little information was available to set quantitative guidelines for normal selenium concentrations in eggs of wild birds (i.e., in eggs of birds not exposed to selenium-enriched environments). By the mid-1980's slightly more information was available, and based on that information Ohlendorf (1989) suggested that normal concentrations averaged about 1 to 3 p/m selenium. Three dozen reference values for mean egg selenium in wild birds were available by the late 1980's, allowing Ohlendorf and Skorupa (1989) to estimate the reference interquartile boundaries as 1.4 and 2.7 p/m. This agreed with Ohlendorf's (1989) original estimate of normal concentrations. More recently, the reference data for wild birds inhabiting nonmarine wetlands have expanded to 74 sample means that allow a detailed percentile table to be constructed (table 1).

Table 1. Percentile values for mean selenium concentrations in samples of bird eggs from uncontaminated nonmarine wetlands (N = 74 sample means).

Percentile	*Mean Selenium Concentration*[a] *(p/m, dry weight)*
10th	1.0
20th	1.3
25th	1.4
30th	1.4
40th	1.6
50th (Median)	1.9
60th	2.0
70th	2.3
75th	2.4
80th	2.5
85th	2.8
90th	2.9

[a]The extreme sample means were 0.6 and 7.8 p/m. Sample means were typically based on samples of 2 to 9 individual eggs. Thus, the percentile values are approximate and apply only to means from small samples of eggs. As per the central limit theorem (e.g., DeGroat 1975:227), however, the median is valid for comparison to individual eggs or means from any size sample. At background concentrations, arithmetic and geometric means are practically equivalent, however, this table is best suited for comparison against geometric means from contaminated sites.

Sources: Haseltine et al. (1981,1983), Henny and Herron (1989), Hothem et al. (unpubl. data), Kepner et al. (unpubl. data), K. King (pers. comm.), Lambing et al. (1988), Ohlendorf et al. (unpubl. data), Ohlendorf and Marois (1990), Ohlendorf and Skorupa (1989), S. Schwarzbach (pers. comm.), Skorupa et al. (unpubl. data), USFWS (1989).

Significantly, the reference interquartile boundaries have changed very little (from 1.4-2.7 to 1.4-2.4 p/m selenium) with a doubling of the available data base and an increase in the taxonomic and geographic coverage. This suggests that the current reference interquartile boundaries are widely applicable taxonomically and geographically. More than 90 percent of all reference sample means are below 3 p/m selenium (table 1). Thus, > 3 p/m mean egg selenium seems to be a reasonable indicator threshold for avian contamination in nonmarine environments. In the Tulare Basin, avian contamination (i.e., mean egg selenium > 3 p/m) is associated with evaporation ponds containing as little as 1 to 3 p/b waterborne selenium (tables 2 and 3).

TOXIC CONCENTRATIONS OF SELENIUM IN EGGS OF WILD BIRDS

Selenium toxicity, as indicated by abnormally high rates of teratogenesis (i.e., embryo deformity, particularly multiple overt deformities; Hoffman et al., 1988 and Hoffman and Heinz, 1988) or embryo death, was observed in several populations of waterbirds at Kesterson and at evaporation ponds in the Tulare Basin (Ohlendorf and Skorupa, 1989 and Skorupa et al., unpubl. data). Teratogenic populations averaged from about 15 to 80 p/m egg selenium. Assessments of average egg selenium and embryo status at Kesterson (northern San Joaquin Valley; Ohlendorf and Skorupa, 1989 and Ohlendorf et al., unpubl. data), in the Grassland Water District (northern San Joaquin Valley; R. L. Hothem et al., U.S. Fish and Wildlife Service, unpubl. data), in the Tulare Basin (southern San Joaquin Valley; Ohlendorf and Skorupa, 1989 and Skorupa et al., unpubl. data), and outside the San Joaquin Valley (Stephens et al. 1988 - Utah; Henny and Herron, 1989 - Nevada; S. G. Schwarzbach et al., U.S. Fish and Wildlife Service, unpubl. data - California/Oregon; D. U. Palawski et al., U.S. Fish and Wildlife Service, unpubl. data - Montana; P. Ramirez et al., U.S. Fish and Wildlife Service, unpubl. data - Wyoming) yield a clear dose-response relationship (figure 1).

A distinct dose-response relationship is evident in figure 1 (Spearman rank correlation = 0.943; N=6; $p < 0.05$; Siegel, 1956) despite a relatively coarse (but unambiguous) measure of contaminant response (presence or absence of overt deformities in a sample of embryos), uneven embryo sampling effort, multiple bird species, and the diversity of chemical environments represented, all of which are expected to weaken the dose-response graph. This dose-response relationship generated from field sampling (figure 1) suggests a teratogenesis threshold between 13 and 24 p/m mean egg selenium. One experimental study that exposed game-farm mallards (*Anas platyrhynchos*) to dietary selenomethionine, a form of selenium that seems to be an excellent model for environmental exposure (Hamilton et al., 1990), suggests that the teratogenesis threshold lies between 12 and 37 p/m mean egg selenium (Hoffman and Heinz, 1988 and Heinz et al., 1989). Mean egg selenium as high as about 25 p/m is associated with waterborne selenium as low as 10 to 20 p/b in the Tulare Basin (table 2).

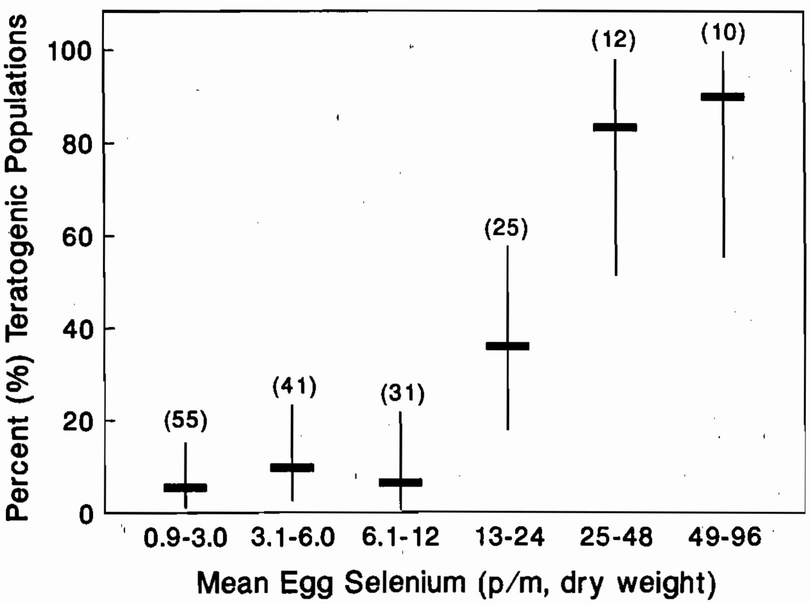

Figure 1. Dose-response relationship between mean egg selenium and teratogenic classification of aquatic bird populations.

Dose intervals were delineated so that the first interval encompasses normal concentrations of mean egg selenium, and the succeeding intervals form a geometric progression. For each dose interval the observed percent of populations classified as teratogenic is plotted along with 95 percent binomial confidence intervals. Sample sizes (number of populations assessed) for each dose interval are listed above the response plots. Note, this plot is a population level analysis and cannot be used to infer the probability of teratogenesis in individual eggs of known selenium content.

Another response variable for embryotoxicity is egg hatchability (e.g., see Ohlendorf et al., 1989). Hatchability is a more sensitive response variable than overt teratogenesis, but, in principle, it is also more ambiguous because of its equal sensitivity to noncontaminant-related perturbations (such as hen nutrition, unusual weather, observer disturbance, etc.). In practice, results of artificial incubation studies with eggs of black-necked stilts (Himantopus mexicanus) and American avocets (Recurvirostra americana) indicate that nearly all hatchability depression at evaporation ponds is contaminant-induced (Skorupa et al., unpubl. data).

Ohlendorf et al. (1986) related embryonic selenium exposure to embryo viability (= egg hatchability) for individual eggs of American coots (Fulica americana) and black-necked stilts at Kesterson and a reference site. The resulting regression for stilt eggs suggested that the minimum probability (i.e., lower 95 percent confidence band) of hatching failure started increasing sharply at about 10 p/m egg selenium. A similar evaluation of the regression for coot eggs is not possible because of the lack of low-selenium samples.

Preliminary population-level data from the Tulare Basin suggest that significantly reduced hatchability is associated with average selenium concentrations of about 8 p/m or greater (Skorupa et al., unpubl. data). This preliminary threshold value is based on monitoring the reproductive performance of 17 black-necked stilt and American avocet breeding aggregations during 1987 and 1988. Low hatchability was documented in eight of nine populations with mean egg selenium > 8 p/m, but in only two of eight populations with mean egg selenium < 8 p/m. Note that the Tulare preliminary analysis is a population-level analysis, and that the populations averaging 8 p/m or more egg selenium include individual eggs with > 10 p/m selenium (Skorupa et al., unpubl. data). Thus the individual-level analysis of Kesterson data and the population-level analysis of Tulare data seem compatible. The lowest concentration of waterborne selenium associated with populations of stilts or avocets over the 8 p/m mean egg selenium threshold is 10 p/b. Eggs of snowy plovers (Charadrius alexandrinus) and eared grebes (Podiceps nigricollis), however, have averaged 7 to 8 p/m selenium at ponds in the Tulare Basin with as little as 2 to 3 p/b waterborne selenium (table 3 and Skorupa et al., unpubl. data).

SELENIUM BIOACCUMULATION: FROM WATER TO THE AVIAN FOOD CHAIN

Studies at evaporation ponds in the Tulare Basin and at lakes and ponds in Colorado and Wyoming demonstrated strong correlations between concentrations of selenium in the water and in aquatic plants and insects (Birkner, 1978 and Shelton et al., 1990). Data for waterborne selenium and food-chain selenium from the Tulare Basin yield statistically significant correlation coefficients of 0.91 to 0.98 for widgeon grass (Ruppia maritima), water boatmen (Corixidae), brine shrimp (Artemia franciscana), midge fly larvae (Chironomidae), and damselflies (Zygoptera) (J. Shelton et al., California Department of Water Resources, unpubl. data). At typical bioaccumulation factors of 1,000 to 5,000 (Birkner, 1978 and Schuler, 1987) for normal concentrations of waterborne selenium (i.e., < 1 p/b; Schroeder et al., 1988), samples of uncontaminated aquatic invertebrates should usually average < 4 p/m selenium (Ohlendorf, 1989). Results summarized in table 2 suggest that corixids, a common aquatic insect in evaporation ponds, begin to bioaccumulate selenium to concentrations averaging > 4 p/m at a waterborne selenium concentration between about 2 and 10 p/b.

SELENIUM BIOACCUMULATION: FROM THE DIET (I.E., AVIAN FOOD CHAIN) TO THE EGG

Ohlendorf (1989) reported that bird eggs generally contain concentrations of selenium that are 1 to 3 times the dietary exposure of breeding females. Studies relating egg selenium to precisely verified levels of dietary exposure in the field have not been conducted. Heinz et al. (1989) experimentally exposed game-farm mallards to selenomethionine and demonstrated that egg selenium is closely related to a hen's dietary exposure. This has also been reported in the poultry literature (see citations in Heinz et al., 1989 and Ohlendorf, 1989). In the mallard experiment, average egg selenium varied from about 2.5 to 4.0 times the dietary exposure (dry weight basis). If biologically incorporated organoselenium consumed in the wild is assimilated with similar efficiency as dietary supplements of selenomethionine in the lab, a dietary intake averaging roughly 5 p/m organoselenium leads to an average egg selenium of about 15 p/m, the lowest mean concentration of egg selenium associated with embryo teratogenesis at Kesterson.

Much lower diet-to-egg bioaccumulation factors of 0.10 to 0.18 have been experimentally demonstrated for diets supplemented with inorganic forms of selenium (Heinz et al., 1987). However, evidence suggests that the selenium content of natural foods is predominantly in the form of organoselenium (Boyum and Brooks, 1988 and Hamilton et al., 1990). The diet-to-egg bioaccumulation factors of 1 to 3 implied by the field data presented in table 2 indicate substantial dietary exposure to organoselenium, although dietary exposure in the field likely includes a mixture of inorganic and organic forms of selenium.

A critical dietary threshold of about 5 p/m is consistent with the findings of Heinz et al. (1989) and Smith and Heinz (1990) for mallards. They found that the dietary threshold for elevated embryo teratogenesis (and reduced hatchability) was between 4 and 7 p/m of selenium as selenomethionine. If 80 percent of the selenium in natural foods is organoselenium (Boyum and Brooks, 1988), then toxic contamination of the food chain occurs between about 2 and 13 p/b waterborne selenium in Tulare evaporation ponds (estimated from unpublished regression equations for food-chain selenium available from John Shelton, California Department of Water Resources, Fresno, CA; for brine shrimp equation see figure 3).

WATERBORNE SELENIUM AS A PREDICTOR OF EGG SELENIUM

Because measures of egg selenium are relatively precise indicators of the potential for adverse biological effects, identification of a quantitative relationship between waterborne selenium and egg selenium would be extremely desirable. However, waterborne selenium only determines the potential for selenium bioaccumulation in bird eggs (hereafter cited as "potential egg selenium"). Many variables are interposed between waterborne selenium and egg selenium (figure 2) that can alter the actual bioaccumulation of selenium (hereafter cited as "realized egg selenium"). Consequently, waterborne selenium is often an imprecise predictor of realized egg selenium (table 2).

The four sites listed in table 2 exhibit distinctly separated concentrations of waterborne selenium. Even though between-site separation in mean corixid (food-chain) contamination is distinct, only the lowest selenium site (TLDD-N) can be separated clearly from other sites on the basis of mean selenium concentrations in bird eggs (i.e., on the basis of "realized egg selenium"). Essentially, overlap in the spread of species' means for realized egg selenium is substantial when waterborne selenium (on a total recoverable basis) is anywhere between about 10 and 350 p/b (table 2).

Data for corixids (table 2) are consistent with the general finding (previously cited) that waterborne selenium strongly predicts food-chain selenium. Thus, in figure 2, the variables between step 1 (water selenium) and step 4 (food-chain selenium) must be fairly constant within the San Joaquin Valley and must not be responsible for the confounding results for realized egg selenium. Likewise, within species, variables between step 5 (avian exposure) and step 7 (egg selenium) should be constant. Hence, the variable between step 4 and step 5, avian behavioral ecology, may be the primary source of confounding variation.

Ecologically mediated behavioral characteristics such as degree of residency, home-range size, habitat preferences, and food preferences are very flexible between and within species. These variables may determine whether a site's potential for selenium bioaccumulation, based on waterborne selenium,

(1) Concentration of Contaminant in Water (1)

↓ **Geochemical and Microbiotic Environment** ↓

(2) Bioavailability of Contaminant to Macrobiota (2)

↓ **Food Chain Behavioral Ecology** ↓

(3) Food Chain Exposure to Contaminant (3)

↓ **Food Chain Physiology** ↓

(4) Food Chain Uptake of Contaminant (4)

↓ **Avian Behavioral Ecology** ↓

(5) Avian Exposure to Contaminant (5)

↓ **Avian Digestive Physiology** ↓

(6) Avian Uptake of Contaminant (6)

↓ **Avian Reproductive Physiology** ↓

(7) Concentration of Contaminant in Eggs (7)

Figure 2. Major variables potentially confounding the relationship between waterborne selenium and egg selenium.

In this simplistic representation of a water-to-egg contaminant pathway, movement between each step of the path is potentially influenced by an interposed variable (bold type enclosed by boxes).

Table 2. Geometric mean selenium concentrations (and number of samples analyzed) of corixids (an aquatic insect) and bird eggs relative to waterborne selenium at four evaporation pond systems in the San Joaquin Valley, California.

			← *Kesterson*[c]	
	TLDD-N[a]	*TLDD-S*[b]	*Reservoir*	*WFarm*[d]
Water *(total recoverable, p/b)*	1.1 - 2.5	9.8 - 23	(65 - 225)	140 - 345
Corixids (p/m, dry wt.)	3.4 (9)	13 (6)	22 (13)	38 (6)
Eared Grebe Eggs *(p/m, dry wt.)*		23 (9)	70 (18)	79 (5)
American Coot Eggs			32 (17)	
Waterfowl Eggs:				
Gadwall	2.9 (17)	20 (9)	20 (22)	
Mallard	1.8 (21)	15 (3)	12 (21)	
Cinnamon Teal	1.9 (31)	20 (7)	11 (12)	
Northern Pintail	2.6 (6)	25 (3)	13 (1)	
Redhead	3.4 (6)	26 (4)		
Ruddy Duck		13 (1)		
Canvasback		10 (4)		
Shorebird Eggs:				
Black-necked Stilt	2.6 (15)	13 (20)	32 (124)	24 (39)
American Avocet	3.7 (13)	12 (10)	19 (60)	22 (40)
Snowy Plover		23 (12)	21 (1)	25 (1)
Killdeer			41 (32)	
Range of Species Means for Egg Selenium	1.8 - 3.7	10 - 26	11 - 70	22 - 79

Note: The National median for mean selenium concentration in samples of bird eggs from uncontaminated reference sites is 1.9 p/m (table 1). Medians for all taxonomic and geographic subgroups within the reference data are in the range 1.0 to 3.0 p/m (Skorupa et al., unpubl. data).

[a]Tulare Lake Drainage District - North: Waterborne selenium is for June, 1987 (Westcot et al., 1988a). Corixid selenium is for September, 1988 (Moore et al., 1989). Bird egg selenium is for April-July, 1987 and/or 1988 (Ohlendorf and Skorupa, 1989 and Skorupa et al., unpubl. data).

[b]Tulare Lake Drainage District - South: Waterborne selenium is for June, 1987 (Westcot et al., 1988a). Corixid selenium is for June 1987 (Moore et al., 1989). Bird egg selenium is for April-July, 1987 and/or 1988 (Ohlendorf and Skorupa, 1989 and Skorupa et al., unpubl. data).

[c]Kesterson Reservoir: Waterborne selenium is for May, 1983 (Saiki and Lowe, 1987) and May, 1984 (Schuler 1987) with an appropriate conversion from dissolved basis to approximate total recoverable basis (see footnote g in table 3). Corixid selenium is for May, 1983 (Saiki and Lowe, 1987), May 1984 (Schuler, 1987) and April-June, 1985 (Hothem and Ohlendorf, 1989). Bird egg selenium is for April-June, 1983 and/or 1984 and/or 1985 (Ohlendorf and Skorupa, 1989 and Ohlendorf et al., unpubl. data), except for snowy plover which is for April-June 1986 (F.L. Paveglio, unpubl. data).

[d]Westfarmers: Waterborne selenium is for June, 1987 (Westcot et al., 1988a).Corixid selenium is for June 1987, and June 1988 (Moore et al., 1989). Bird egg selenium is for April-July, 1987 and/or 1988 (Ohlendorf and Skorupa, 1989 and Skorupa et al., unpubl. data).

will be fully or only partially realized. For example, the counter-intuitive finding that waterfowl eggs from TLDD-S were equally or more contaminated than waterfowl eggs from Kesterson (table 2) is probably due to ecologically mediated behavioral variation. TLDD-S is isolated within an intensively developed agricultural landscape mostly devoid of nondrainwater wetlands during the spring. Kesterson was in a landscape with abundant neighboring wetlands that contained considerably lower concentrations of selenium (Ohlendorf et al., 1987). Thus, ducks at Kesterson had opportunities to use habitat that would reduce exposure to drainage-water contaminants whereas ducks at TLDD-S did not. This interpretation is supported by the results (table 2) for eared grebes (a very sedentary forager during the breeding season) that suggest duck eggs at TLDD-S were representative of local contaminant conditions, whereas duck eggs at Kesterson may have realized only 15 to 30 percent of the site potential for bioaccumulating selenium.

Because of eared grebes' long residency time (they are usually the latest breeders; C. J. Henny, U.S. Fish and Wildlife Service, pers. comm.; pers. obser.), localized foraging range (most foraging on evaporation pond systems is done in the same cell as the nest colony; pers. obser.), and stereotyped food preferences (for aquatic invertebrates; Johnsgard, 1987), grebes may consistently come the closest to realizing the full potential for selenium bioaccumulation in eggs at any site (i.e., realized egg selenium may often equal potential egg selenium). Eared grebes probably come close to meeting the special circumstances required for a one-to-one correspondence between steps 4 and 5 (in figure 2). This correspondence, in turn, best meets the special condition for predicting egg selenium from waterborne selenium:

$$[1]\quad \text{If,}\ \text{Log}(FCS) = a + b\,\text{Log}(WS)$$

$$[2]\quad \text{and,}\ \text{Log}(MES) = c + d\,\text{Log}(DS)$$

$$\text{and,}\ FCS = DS\ \text{(the special condition)}$$

$$\text{then,}\ \text{Log}(MES) = c + d[a + b\,\text{Log}(WS)] = (c + da) + db\,\text{Log}(WS)$$

$$[3]\quad = e + f\,\text{Log}(WS)$$

where,
- DS = p/b dry weight dietary selenium
- FCS = p/b dry weight food-chain selenium
- MES = p/b dry weight arithmetic mean egg selenium
- WS = p/b total recoverable waterborne selenium
- a-d = fitted regression parameters
- e = (c + da)
- and, f = db.

Based on different taxa of aquatic invertebrates, Shelton et al. (unpubl. data) calculated four estimates of equation [1] for evaporation ponds in the Tulare

Basin. An estimate of equation [2] can be calculated from Heinz et al.'s (1989) data for game-farm mallards. This results in the following four solutions for equation [3]:

[4] Log (MES) = 3.86 + 0.57 Log (WS) (based on corixids)
[5] Log (MES) = 3.66 + 0.57 Log (WS) (based on brine shrimp)
[6] Log (MES) = 4.07 + 0.72 Log (WS) (based on midge larvae)
[7] Log (MES) = 3.81 + 0.67 Log (WS) (based on damselflies)

Predicted (from equations [4]-[7]) and observed mean egg selenium for eared grebes in the San Joaquin Valley can be compared (table 3). The performance of equation [5] is particularly encouraging, because the average absolute difference between predicted and observed mean egg selenium was only 6 percent. More importantly, the differences between predictions and observations were < 10 percent in the critical lower range of waterborne selenium (i.e., < 20 p/b) that is likely to embrace important biological thresholds.

Although brine shrimp are a highly preferred food of eared grebes in saline environments (Jehl, 1988), brine shrimp apparently do not occur at the nesting sites listed in table 3 (Hothem and Ohlendorf, 1989 and D. A. Barnum, U.S. Fish and Wildlife Service, pers. comm.); thus, there is no obvious reason for the brine-shrimp-based regression equation [5] to perform so well. Perhaps the bioavailable (for transfer to bird eggs) organoselenium concentrations biologically incorporated into macroinvertebrate tissues do not vary much between species (within a pond), and measures of total recoverable selenium from brine shrimp most closely estimate the bioavailable organoselenium fraction. Unlike corixids, midges, and damselflies, brine shrimp do not have a well-developed chitinous exoskeleton to which confounding fractions of inorganic selenium can become externally adsorbed (Krantzberg and Stokes, 1988 and Newman and McIntosh, 1989). The fact that all the other equations tend to overestimate mean egg selenium is consistent with this interpretation. Or perhaps brine shrimp are very representative of the modal type of aquatic invertebrate (i.e., nonchitinous, water column dwelling) preferred by eared grebes in saline environments even where brine shrimp are not available (Mahoney and Jehl, 1985). Future studies will have to further test the reliability of the brine-shrimp-based predictive model and, if it continues to prove reliable, focus on elucidating exactly why it performs so well.

One of the biological thresholds of inherent interest is the contamination threshold, that is, the concentration of waterborne selenium associated with a potential for mean egg selenium of about 3 p/m (the threshold between background and contaminated eggs). Ideally, the management goal for all wetlands is to keep waterborne selenium under the contamination threshold.

Table 3. Comparison of observed and predicted mean egg selenium for eared grebes nesting on evaporation ponds in the San Joaquin Valley, California.

Site	*Waterborne Se*[a] *(p/b)*	*Mean Egg Se (p/m)* *Observed (N)*	*Predicted*[b] *corix*	*brshp*	*mdlve*	*damfy*
Lost Hills Ranch	2.8[c]	8.5[d] (7)	13	8.2	25	13
TLDD - South	15[e]	23[f] (9)	34	21	83	40
Kesterson Reservoir	(126)[g]	75[h] (13)	114	72	382	165
Westfarmers	176[i]	81[j] (5)	138	87	486	206
Average Absolute Difference from Observed:			56%	6%	341%	100%

[a]On a total recoverable selenium basis.
[b]Predicted values (arithmetic means) are from equations 4-7 of text which were based on food-chain data for corixids (corix), brine shrimp (brshp), midge fly larvae (mdlve), and damselflies (damfy). The observed values are also arithmetic means and therefore do not always match the geometric means reported from the same data in table 2.
[c]Measured in pond 1 during June, 1988 (Westcot et al., 1988b).
[d]Measured in eggs from pond 1 during June and July, 1988.
[e]Measured in pond 4 during June, 1988 (Westcot et al., 1988b).
[f]Measured in eggs from pond 4 during June and July, 1988.
[g]Saiki and Lowe (1987) measured 68 p/b dissolved selenium in pond 11 during May, 1983. That measurement has been multiplied by a factor of 1.85 to convert it to an approximate total recoverable selenium basis. Fujii (1988) reported an average ratio of 1.85 for total recoverable selenium to dissolved selenium in a Tulare Basin evaporation pond system. Moore et al. (1990) reported an aggregate ratio of 1.98 for Kesterson water analyses, but that is not based on a matched set of split samples as are Fujii's ratios.
[h]Measured in eggs from pond 11 during 1983.
[i]Measured in pond 1 during June, 1988 (Westcot et al., 1988b).
[j]Measured in eggs from pond 1 during June, 1988.

From equation [5] a concentration of about 0.5 p/b waterborne selenium has the potential to result in mean egg selenium of about 3,000 p/b (= 3 p/m). This prediction can be compared to field data from Foxtail Lake and Carson Lake of the Stillwater Wildlife Management Area, Nevada. Eared grebe eggs collected from Foxtail Lake averaged 3.4 p/m selenium (N=10; C. J. Henny, unpubl. data) when waterborne selenium was < 1.0 p/b (R. J. Hoffman, U.S. Geological Survey, unpubl. data). Eared grebe eggs sampled from Carson Lake averaged 2.3 p/m selenium (N=11; C. J. Henny, unpubl. data) when waterborne selenium also was < 1.0 p/b (Hoffman et al., 1990). Thus, these field data suggest that eared grebe eggs cross over the 3.0 p/m mean selenium threshold between 0.0 and 1.0 p/b waterborne selenium which is consistent with the prediction generated from equation [5].

An estimate of uncertainty associated with the prediction of a contamination threshold at 0.5 p/b cannot be obtained through routine least squares estimates of variance because equation [5] was derived algebraically. A rough estimate of uncertainty, however, can be obtained by a graphical procedure (figure 3). Point B in figure 3 is derived from the lower 95 percent confidence band of the diet-to-egg regression equation, and it therefore is a rough estimate of the maximum mean dietary selenium consistent with a mean egg selenium of 3 p/m (point A). Similarly, point C in figure 3 is a rough estimate of the maximum waterborne selenium that can be linked with point A through point B. Thus point C is an estimate of the maximum waterborne selenium consistent with a mean egg selenium of 3 p/m, given the variation associated with the two empirical regression equations that equation [5] was algebraically derived from. Point C is estimated as 2.3 p/b waterborne selenium (figure 3). Consequently, the prediction of a contamination threshold at 0.5 p/b waterborne selenium is associated with a relatively narrow range of uncertainty ranging up to about 2.3 p/b.

A more direct approach to estimate the contamination threshold and its uncertainty is to derive an empirical least squares regression equation relating potential mean egg selenium to waterborne selenium directly from the four data points for eared grebes presented in table 3. This yields a regression equation of Log (MES) = 3.69 + 0.55 Log (WS) [R-squared = 0.997; p = 0.001] and a predicted contamination threshold of 0.4 p/b waterborne selenium with 95 percent confidence limits of 0.1 to 0.9 p/b (estimation of X from Y; Sokal and Rohlf 1981:496). The drawbacks of this approach are that the contamination threshold and its confidence limits are extrapolations outside the range of the four data points, and the regression from those four points is not as likely as the graphical approach of figure 3 to fully represent the variation embraced by San Joaquin Valley evaporation ponds. The graphical approach is based on larger sample sizes covering a wider range of environmental conditions (including the crucial threshold region). Both approaches, with low uncertainty, yield a maximum likelihood estimate of about 0.5 p/b waterborne selenium for the contamination threshold.

IMPLICATIONS FOR DRAINAGE-WATER MANAGEMENT

Based on best available estimates of several critical thresholds (summarized in table 4), there is a fairly narrow range of about 0.5 to 20 p/b waterborne selenium between the minimum estimate for the contamination threshold (for eggs) and the maximum estimate for the embryotoxicity threshold. Many

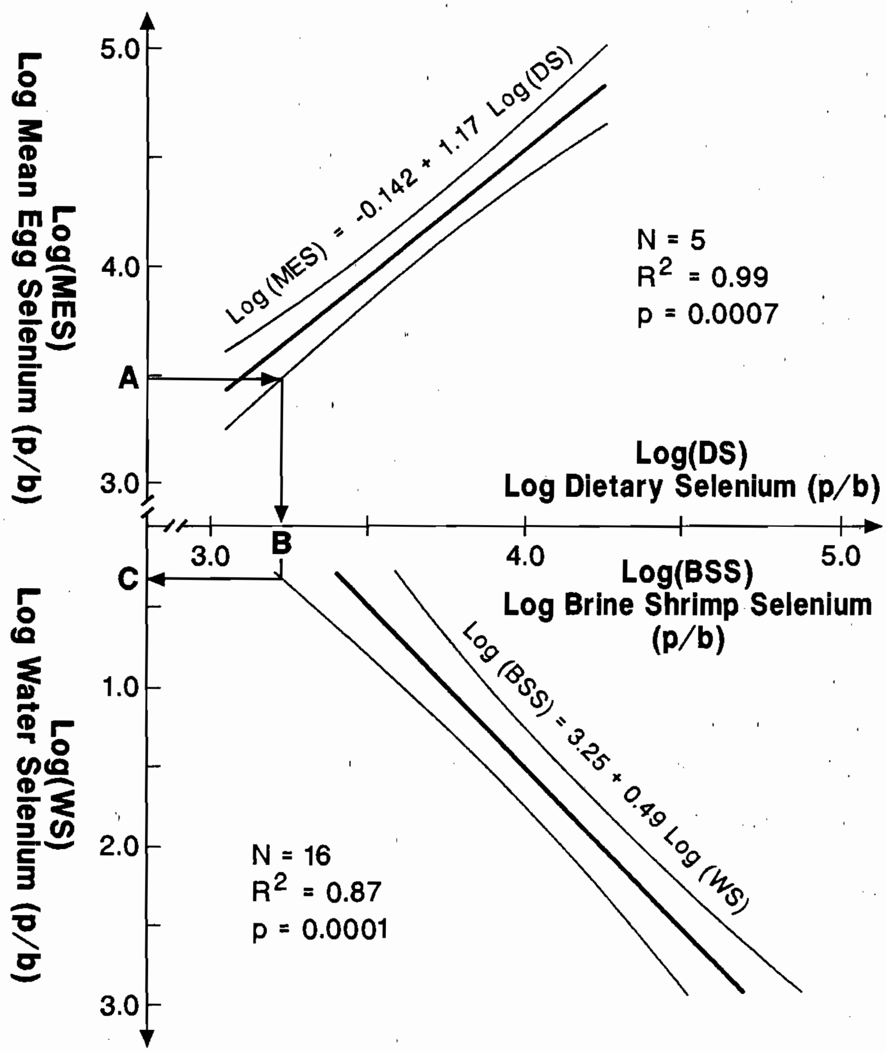

Figure 3. Graphical estimate of the uncertainty associated with predicting the avian contamination threshold for waterborne selenium through separate regressions for food chain uptake and avian uptake of selenium.

In this figure, the lower 95 percent confidence bands of two regression equations are utilized to estimate the maximum concentration of waterborne selenium (point C) consistent with the bioaccumulation of 3 p/m mean egg selenium (point A) by waterbirds. The estimate of point C is 2.3 p/b waterborne selenium (total recoverable). See text for additional explanation.

Table 4. Summary of estimated risk thresholds for selenium .

Estimated Thresholds	*Criterion*
Waterborne Selenium (p/b total recoverable)	*Contamination Thresholds*
0.5	From equation [5] for eared grebe eggs.
< 1.0	Observed for eared grebe eggs from Stillwater Wildlife Management Area, NV.
1 - 3	Observed for eggs of several species of aquatic birds from the Tulare Basin, CA.
	Embryotoxicity Thresholds
2 - 13	Based on critical dietary threshold of ca. 5 p/m organoselenium and empirically derived bioaccumulation curves for total selenium in food-chain items from Tulare Basin evaporation ponds.
10 - 20	Based on minimum waterborne selenium associated with mean egg selenium > 24 p/m in the Tulare Basin, CA.
Egg Selenium (p/m, dry weight)	*Contamination Threshold*
3.0	Upper boundary for normal <u>mean</u> egg selenium estimated from field sampling for various species of waterbirds at Nationwide reference sites.
	Embryotoxicity Threshold
8.0	Approximate lower boundary for <u>mean</u> egg selenium associated with populations of black-necked stilts and American avocets exhibiting impaired egg hatchability in the Tulare Basin, CA.
10	Approximate lower boundary for <u>individual</u> egg selenium associated with impaired embryo viability among black-necked stilts at Kesterson Reservoir, CA.
13 - 24	Threshold range for <u>mean</u> egg selenium associated with teratogenic populations of aquatic birds sampled in western and northern plains states.
12 - 37	Threshold range for <u>mean</u> egg selenium associated with impaired egg hatchability and elevated incidence of teratogenesis in mallard embryos when diets of mallard hens are supplemented with selenium in the form of selenomethionine.

factors can influence whether the full potential for bioaccumulation of selenium in eggs (associated with any given concentration of waterborne selenium) will be realized. Although in many cases local site conditions and the idiosyncrasies of avian behavior may keep realized egg selenium below the site's full potential, it would be prudent to consider drainage water containing 3 to 20 p/b selenium as peripherally hazardous to aquatic birds (i.e., hazardous to some species under some environmental conditions) and drainage water containing more than 20 p/b selenium as widely hazardous to aquatic birds (i.e., hazardous to most species under most environmental conditions; table 4 and equation [5]).

Because impounded drainage water in the Tulare Basin averages roughly 50 p/b selenium (Moore et al., 1990), the protection of aquatic birds is dependent on management actions. Such actions should either reduce the concentrations of contaminants or reduce avian use of contaminated ponds. To prevent most avian toxicity, a reasonable provisional goal for chemical or biological decontamination technologies is purification of drainage water to < 10 p/b waterborne selenium. This goal will not, however, prevent avian contamination. To minimize contamination and the possibility of subtle nonlethal adverse effects and secondary hazards, a reasonable provisional goal is purification to < 2.3 p/b waterborne selenium. When these standards of purity cannot be met by decontamination technology, as is currently the case (Hanna et al., 1990), actions to significantly reduce avian use of contaminated drainage water are necessary.

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