Although the King and Beikman (1974) map is out of print, a digital version of it, created by Schruben and others (1994), is available <http://geo-nsdi.er.usgs.gov/metadata/digital-data/11/metadata.faq.html> and was used for this study to identify the geological units associated with each site where water or sediment samples were collected. A structural and lithologic map of the United States by Bayer (1983) is based on the King and Beikman (1974) map and remains in print.

Upper Cretaceous marine sedimentary rocks are the most widespread geologic source of selenium in the Western United States. These rocks are commonly seleniferous (Lakin and Byers, 1941) and form the bedrock in more than 300,000 mi^2, or 17 percent of the total land area, in the 17 Western States (fig. 20). Soils derived from these fine-grained sedimentary rocks commonly provide good soils for agricultural development and commonly are irrigated in the arid and semiarid regions of the Western United States.

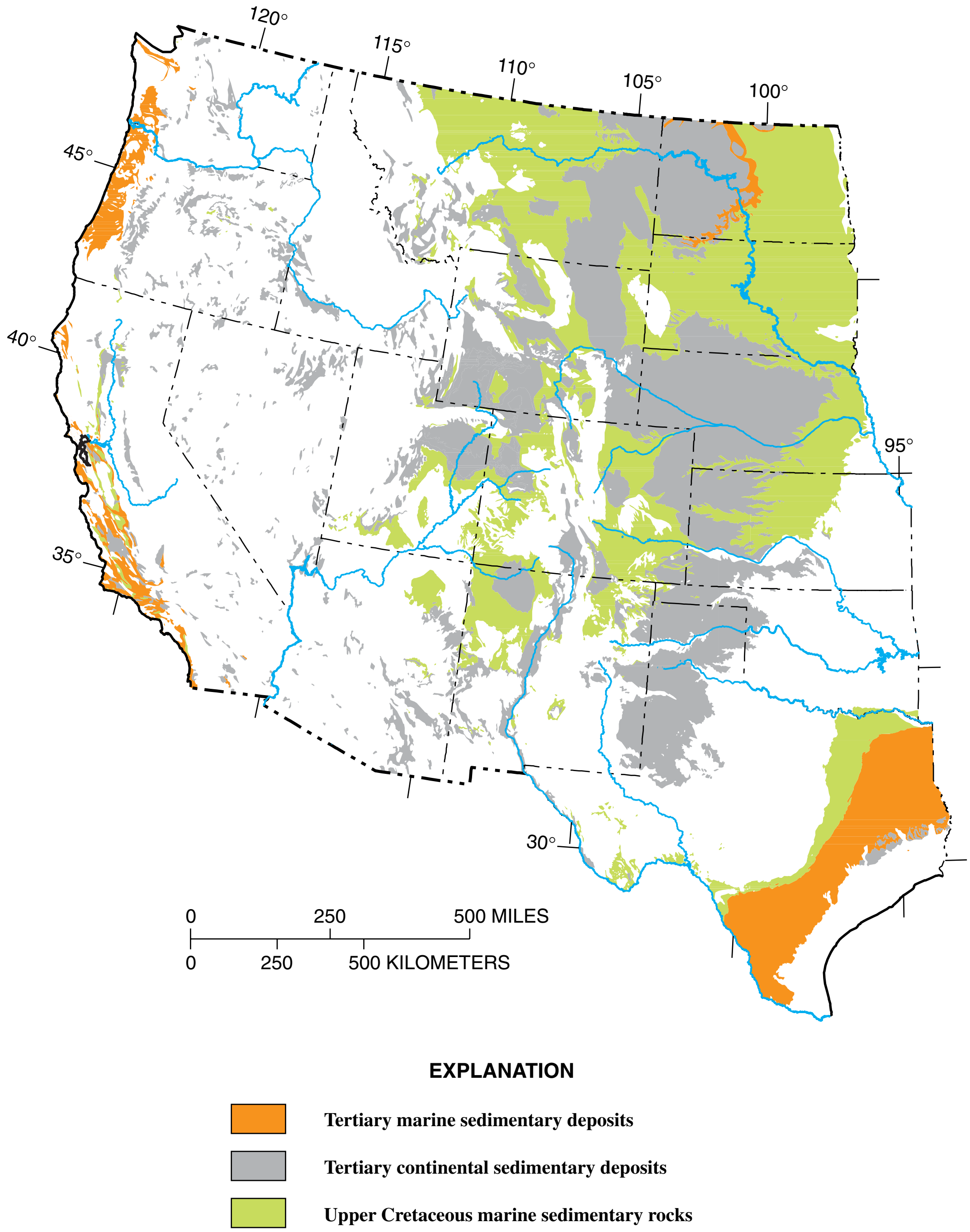


FIGURE 20. Areas in Western United States where potentially seleniferous rocks form bedrock. Geology from King and Beikman (1974). For base credit, see figure 1.

If biological processes are the principal reason for selenium enrichment of marine sediments as Piper (1994) and Presser (1994b) suggest, marine sedimentary deposits of Tertiary age as well as Cretaceous age likely are seleniferous. In the Coast Ranges of California, Presser (1994b) identified Upper Cretaceous–Paleocene, Eocene–Oligocene, and Miocene marine deposits that are seleniferous. In addition to organic selenium concentrated by bioaccumulation, as sea levels declined during the early Tertiary, particulate matter derived by erosion of seleniferous Cretaceous sedimentary deposits exposed during the recession of the sea would have been deposited in the Tertiary marine sediments. Sindeeva (1964) concluded that selenium dissolved and suspended in river water precipitates immediately upon entering the ocean. Marine sedimentary deposits of Tertiary age form the bedrock beneath almost 84,800 mi^2 of land in the Western United States (fig. 20), which is about 4.6 percent of the total land area.

Depending on their history, Tertiary continental sedimentary deposits may be seleniferous. Continental sedimentary deposits of Tertiary age (fig. 20) form the bedrock in about 366,000 mi^2, or about 20 percent of the total land area, in the Western United States.

SOURCES OF SELENIUM IN NATIONAL IRRIGATION WATER QUALITY PROGRAM STUDY AREAS

The map units from the King and Beikman (1974) geologic map are listed in table 16 by study area and are ranked by the number of sites that are within a particular geologic unit in each area. The most common geologic units forming bedrock in each of the study areas range from Cretaceous to Quaternary in age and consist mainly of marine or continental sedimentary deposits.

Of the 26 NIWQP study areas, 12 have sampling sites located where Upper Cretaceous marine sedimentary rocks form near-surface bedrock (table 16). Seventy-fifth percentile selenium concentrations in surface water in these twelve areas (*B, C, E, F, H, M, N, P, R, V, X,* and *Z)* ranged from less than 1 to 73 µg/L (table 15). To further assess the importance of Cretaceous sedimentary rocks in determining the selenium concentration at the NIWQP sites, individual surface-water sites were classified on the basis of their association with Upper Cretaceous marine sedimentary rocks. The most recent selenium value measured at each site was selected to represent the selenium concentration at the site, and box plots of the data were prepared (fig. 21). The importance of Cretaceous sedimentary rocks to selenium concentration is apparent: the median selenium concentration for sites associated with Cretaceous sedimentary rocks is 7 µg/L (range less than 1 to 8,300 µg/L); for sites not associated, the median is estimated to be 0.4 µg/L (range less than 1 to 390 µg/L).

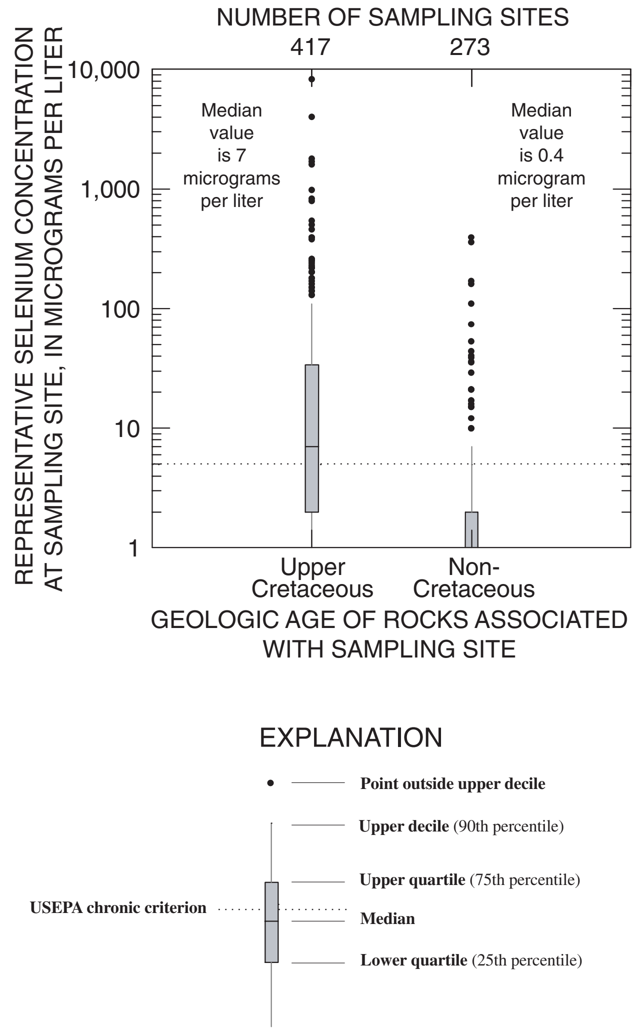


FIGURE 21. Statistical summary of selenium concentrations in filtered surface-water samples showing association of Upper Cretaceous marine sedimentary rocks and elevated selenium concentration. Summary statistics below the reporting limit computed using log-normal maximum-likelihood methods. USEPA, U.S. Environmental Protection Agency. Each surface-water sampling site was represented by the selenium concentration in the most recent non-replicate, filtered sample collected at the site as part of a NIWQP investigation.

TABLE 16. *Generalized bedrock geology of National Irrigation Water Quality Program study areas*

[Geologic units within each study area are ranked according to relative number of individual data-collection sites having indicated geology. Geologic symbols and descriptions used are adapted from compilation by King and Beikman (1974). Generally in decreasing-age order, these geologic units include Early Proterozoic igneous and metamorphic rocks (Xg, granitic rocks; Xm, orthogneiss and paragneiss); upper Paleozoic stratified, mainly marine, sedimentary rocks (uPz); Upper Cretaceous stratified, mainly marine, sedimentary rocks (uK_1, the Woodbine and Tuscaloosa Groups, locally including some Lower Cretaceous rocks not mapped separately; uK_2, the Austin and Eagle Ford Groups; uK_3, the Taylor Group; and uK_4, the Navarro Group); Paleocene continental sedimentary deposits (Txc); Eocene continental sedimentary deposits (Tec); the Eocene Jackson Group (Te_3); Miocene volcanic rocks (Tmf, felsic; Tmv, nonfelsic); Pliocene continental sedimentary deposits (Tpc); Pliocene nonfelsic volcanic rocks (Tpv); thick and widespread Quaternary stratified sedimentary sequences (Q); Quaternary nonfelsic volcanic rocks (Qv); and Holocene stratified sedimentary deposits, Great Plains only (Qh). Geologic units exclude Pleistocene glacial deposits, which blanket large parts of northern interior States]

Study area		Ranked geologic units			
Identifier[1]	**Name**	**1**	**2**	**3**	**4**
A	American Falls Reservoir, Idaho	Q			
B	Angostura Reclamation Unit, South Dakota	uK_3	uK_2	uK_1	
C	Belle Fourche Reclamation Project, South Dakota	uK_2	uK_3		
D	Columbia River Basin, Washington	Q	Tmv		
E	Dolores–Ute Mountain area, Colorado	uK_1	uK_2		
F	Gunnison River Basin–Grand Valley Project, Colorado	uK_2	uK_1		
G	Humboldt River area, Nevada	Q			
H	Kendrick Reclamation Project, Wyoming	uK_2			
I	Klamath Basin Refuge Complex, California–Oregon	Q	Tpv		
J	Lower Colorado River valley, California–Arizona	Q	Xm	Xg	uPz
K	Lower Rio Grande valley, Texas	Qh	Te_3		
L	Malheur National Wildlife Refuge, Oregon	Q	Tmv	Tmf	
M	Middle Arkansas River Basin, Colorado–Kansas	uK_2	uK_3	Q	Tpc
N	Middle Green River Basin, Utah:				
	Ouray subarea	Tec			
	Pariette subarea	Tec	uK_3		
	Stewart subarea	uK_2			
O	Middle Rio Grande, New Mexico	Tpc			
P	Milk River Basin, Montana	uK_3			
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	Q	Tmv	Tpc	
R	Pine River area, Colorado	Tec	uK_4	uK_3	
S	Riverton Reclamation Project, Wyoming	Tec			
T	Sacramento Refuge Complex, California	Q			
U	Salton Sea area, California	Qv			
V	San Juan River area, New Mexico	uK_2	uK_4	Txc	
W	Stillwater Wildlife Management Area, Nevada	Q			
X	Sun River area, Montana	uK_2	uK_3		
Y	Tulare Lake Bed area, California	Q			
Z	Vermejo Project area, New Mexico	uK_3			

[1]Used in figure 2 to show locations of study areas.

Whether lower Tertiary geologic units are large contributors of selenium to the study areas is difficult to assess from the NIWQP data set because there are fewer sites and most of those sites are also associated with Upper Cretaceous geologic units. Of the 26 study areas, 5 include extensive land areas where the surficial rocks are of Paleocene or Eocene age (table 16). Seventy-fifth percentile selenium concentrations in surface water in these five areas (*K, N, R, S,* and *V*) ranged from 1 to 73 μg/L (table 15). Selenium contamination occurs in four of those five areas. Of those four areas, three (*N*, *R*, and *V*) also contain some Upper Cretaceous marine sedimentary rocks, and in the fourth area (*S*), Upper Cretaceous marine sedimentary rocks are found in the uplands adjacent to irrigated lands.

The best evidence of the importance of lower Tertiary geologic units in NIWQP study areas is in the Ouray subarea of the middle Green River Basin (*N*). In the Ouray subarea selenium concentrations in surface water ranged from less than one to 93 μg/L and in ground water ranged from less than one to 9,300 μg/L. All data-collection sites are in areas where Eocene deposits form the bedrock and the nearest exposure of Upper Cretaceous rocks is about 14 mi upstream. Trelease and Beath (1949, p. 80) noted that seleniferous plants occur in parts of the Eocene Uinta Formation, which is exposed in the area (Stephens and others, 1992).

In 6 of the 26 NIWQP areas, selenium is derived mainly from nearby upland source areas or is transported in from great distances upstream in the water used for irrigation. Upper Cretaceous and locally Tertiary marine sedimentary rocks and deposits are found in mountain areas upland from irrigated land in three of these areas (*S, T,* and *Y*), and the water destined for use in irrigation passes over or through Upper Cretaceous or Tertiary marine sedimentary rocks and deposits many miles upstream from irrigated land in the other three areas (*J, K,* and *U*). Seventy-fifth percentile selenium concentrations in surface water in these six areas ranged from less than 1 to 265 μg/L (table 15).

None of the NIWQP areas show evidence of widespread selenium contamination from volcanic sources. Berrow and Ure (1989, p. 221) stated that igneous rocks in general contain low amounts of selenium but that volcanic tuffs (or volcanic ash) in particular may contain much higher amounts. Some of the surficial rocks are volcanic in three of the study areas (*D, I,* and *Q*), and volcanic rocks surround or are upstream from two additional areas (*G* and *W*). Seventy-fifth percentile selenium concentrations in surface water in these five areas ranged from less than 1 to 2 μg/L (table 15).

CLIMATE

The potential for selenium contamination to occur is related to the potential for water to be concentrated by evaporation and to the availability of freshwater to dilute contaminants. A summary of precipitation and evaporation data for the study areas is presented in table 17.

Evaporation data were presented in many ways in the NIWQP reconnaissance- and detailed-studies reports (table 1). Some reports presented evaporation rates but others did not. Some presented Class A pan-evaporation rates, some presented potential evapotranspiration rates, and others presented FWSE rates or water-loss rates from a local reservoir. The FWSE rate was selected to describe evaporation rates (table 17) so that a consistent measure of evaporation could be used for all study areas. Evaporation rates for each area were determined from a map of FWSE rates for the United States (Farnsworth and others, 1982).

A measure of study-area aridity that incorporates information about both evaporation and precipitation rates was chosen because both affect selenium contamination. In the past others used the ratio of evaporation to precipitation to express aridity on climate maps of the United States. Transereau (1905) first used rainfall–evaporation ratios to map climatic zones and to interpret the distribution of forest centers in the Eastern United States. In the current study, a number called the evaporation index (EI) was used; the index was derived by dividing FWSE by precipitation. EI, which essentially is the inverse of Transereau's (1905) rainfall–evaporation ratio, increases as the aridity of an area increases. In the Western United States, because the amount of evaporation is commonly greater than the amount of precipitation, EI typically is greater than 1. In about 56 percent of the land area in the Western United States, the EI is greater than 2.5 (fig. 22); that is, annual evaporation is more than 2.5 times greater than annual precipitation.

HYDROLOGY

EFFECTS OF TERMINAL WATER BODIES ON SELENIUM CONCENTRATIONS

To assess the effect of terminal water bodies on selenium concentrations, lakes, ponds, and marshes in the NIWQP study areas were classified as flow-through or terminal. (Terminal lakes have no outlet, or, defined more narrowly, do not have flow-through on an annual basis.) The selenium value last measured during June–August at each site was selected to represent the selenium concentration at the site. Although the median selenium concentration in terminal water bodies and in flow-through water bodies is nearly the same, 1.0 and 0.8 μg/L respectively (fig. 23), the 75th-percentile selenium concentration for terminal water bodies (24 μg/L) is significantly higher than for flow-through systems (4 μg/L). In flow-through systems, the selenium load is moved through either continuously or episodically, reducing selenium concentrations and thereby ameliorating existing selenium problems or decreasing the potential for selenium problems.

TABLE 17. *Summary description of climate in National Irrigation Water Quality Program study areas*

[Symbols: —, not applicable; <, less than]

Study area		Precipitation (inches)			Free-water-surface evaporation[5] (inches)	Evaporation index[6]	Area ranking[7]
Identifier[1]	Name	Mean annual[2]	Range[3]	Single year[4]			
A	American Falls Reservoir, Idaho	10.9	—	—	41	3.7	17.5
B	Angostura Reclamation Unit, South Dakota	16.4	—	—	46	2.8	22.5
C	Belle Fourche Reclamation Project, South Dakota	14.4	—	—	40	2.8	22.5
D	Columbia River Basin, Washington	8	6 – 10	—	40	5.0	9.5
E	Dolores–Ute Mountain area, Colorado	12	8 – 16	—	53	4.4	13
F	Gunnison River Basin–Grand Valley Project, Colorado	10	8 – 12	—	50	5.4	9.5
G	Humboldt River area, Nevada	5.5	—	—	45	8.1	5
H	Kendrick Reclamation Project, Wyoming	12	—	—	44	3.7	17.5
I	Klamath Basin Refuge Complex, California–Oregon	13	—	—	39	3.0	20.5
J	Lower Colorado River valley, California–Arizona	4.5	<4 – 5	—	85	18.9	2
K	Lower Rio Grande valley, Texas	25.9	21.8 – 30	—	57	2.2	25
L	Malheur National Wildlife Refuge, Oregon	10	—	—	43	4.3	14
M	Middle Arkansas River Basin, Colorado–Kansas	14.6	11.8 – 17.5	—	58	4.0	15
N	Middle Green River Basin, Utah	7.6	—	—	43	5.7	8
O	Middle Rio Grande, New Mexico	9.4	—	—	64	6.8	7
P	Milk River Basin, Montana	12	—	21.4	40	[8]1.9	26
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	9.5	9 – 10	—	43	4.5	12
R	Pine River area, Colorado	14	12 – 16	—	49	3.5	19
S	Riverton Reclamation Project, Wyoming	8.1	—	3.8	40	4.9	11
T	Sacramento Refuge Complex, California	18.5	15 – 22	—	48	2.6	24
U	Salton Sea area, California	3	—	—	73	24.5	1
V	San Juan River area, New Mexico	7.6	6.6 – 8.5	—	56	7.4	6
W	Stillwater Wildlife Management Area, Nevada	5.3	5.2 – 5.4	—	53	10.0	4
X	Sun River area, Montana	12	—	—	36	3.0	20.5
Y	Tulare Lake Bed area, California	5.5	4 – 7	—	61	11.2	3
Z	Vermejo Project area, New Mexico	13.8	—	—	54	3.9	16

[1] Used in figure 2 to show locations of study areas.
[2] As published in reconnaissance and detailed investigation reports (table 1) or midpoint of range if range of values was presented.
[3] As published in reconnaissance and detailed investigation reports (table 1).
[4] Precipitation during year of data collection for study areas where all data were collected during a short period in climatically unusual year. See section "Interrelation of Geology, Climate, and Hydrology," p. 59, in text for discussion.
[5] Determined from map by Farnsworth and others (1982).
[6] Mean annual free-water-surface evaporation divided by mean annual precipitation.
[7] Ranking of study area from most to least arid on the basis of evaporation index.
[8] Calculated using precipitation during year of data collection rather than mean annual precipitation. See section "Interrelation of Geology, Climate, and Hydrology," p.59, in text for discussion.

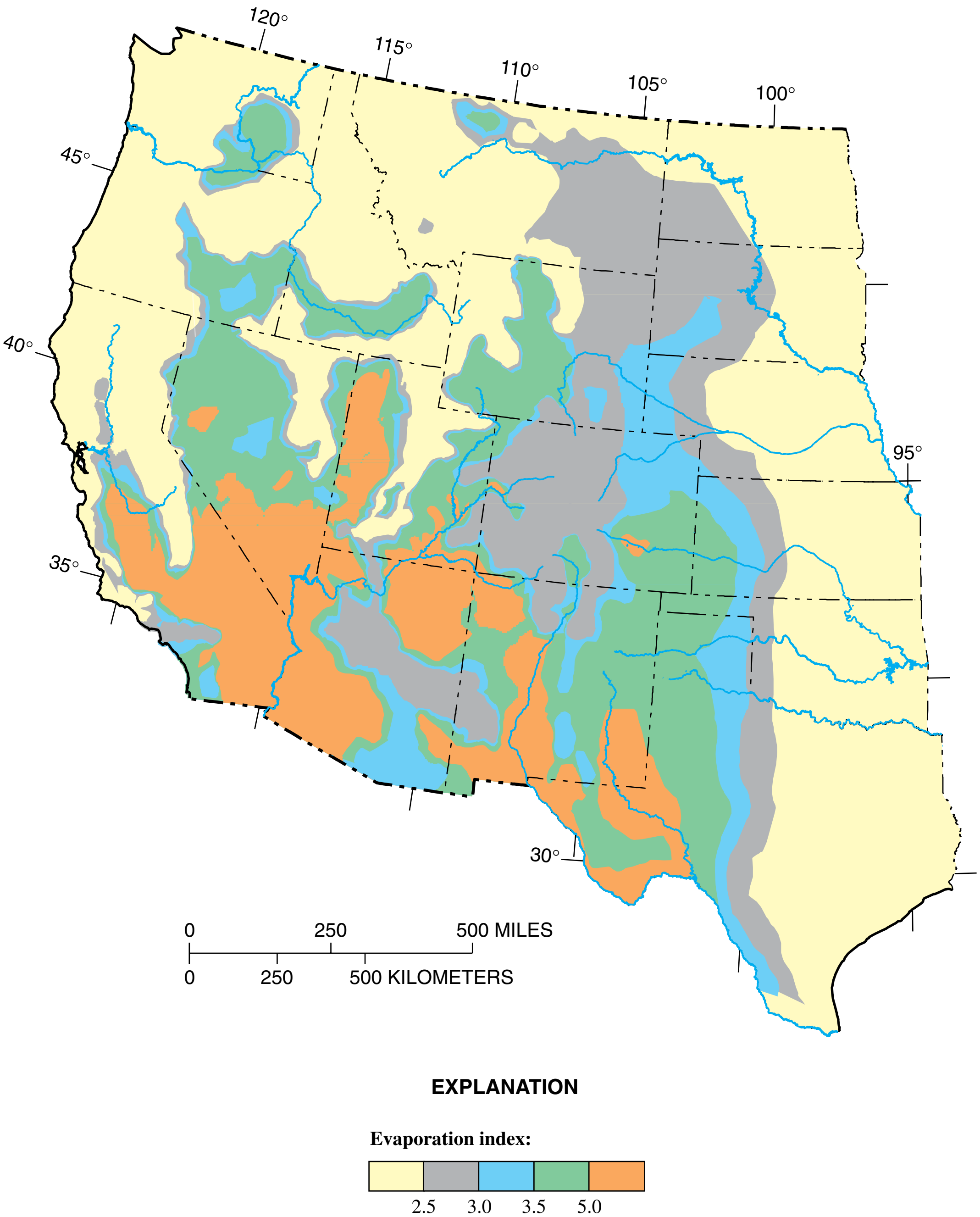


FIGURE 22. Evaporation index in Western United States. Climate data from Farnsworth and others (1982) and G.H. Taylor (Oregon State Climatologist, written commun., 1994). For base credit, see figure 1.

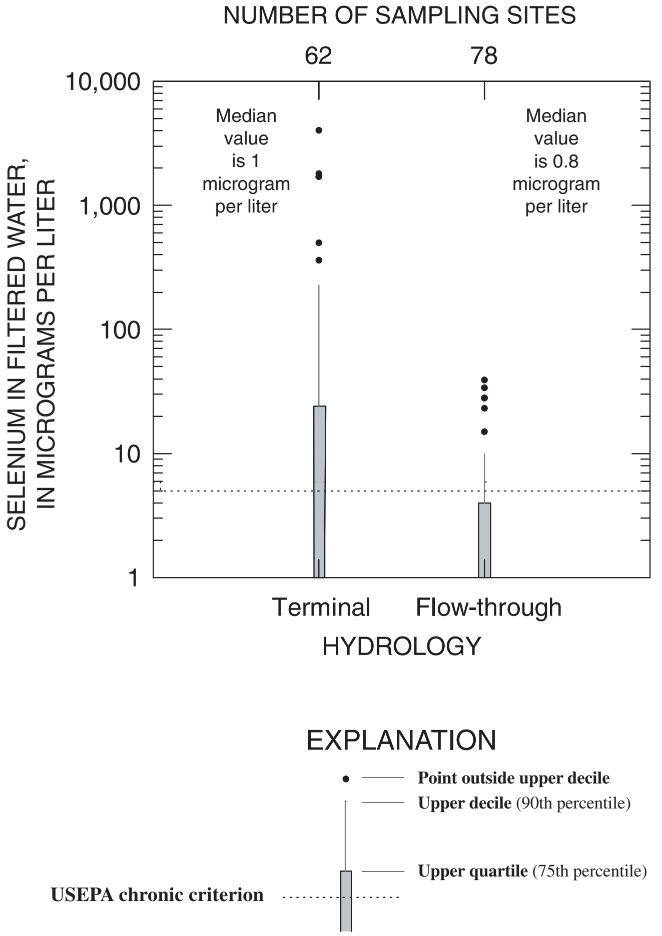


FIGURE 23. Statistical summary of selenium concentrations in filtered surface-water samples from lakes, ponds, and marshes, demonstrating association of elevated selenium concentrations and terminal hydrologic systems. Summary statistics below the reporting limit computed using log-normal maximum-likelihood methods. USEPA, U.S. Environmental Protection Agency. Each lake, pond, or marsh sampling site was represented by the selenium concentration in most recent, non-replicate, filtered sample collected at the site as part of a NIWQP investigation during the months June–August.

Almost two-thirds of the study areas contain individual terminal lakes or ponds, although in most areas, the system as a whole would be considered flow-through. An example of this is Rasmus Lee Lake in the Kendrick Reclamation Project *(H)*. This small lake is terminal but the North Platte River flows through the Kendrick Reclamation Project area.

In the Stillwater Wildlife Management Area and the Salton Sea area *(W* and *U)*, the entire basins are terminal sinks. Within an area, although some lakes may be flow-through and other lakes terminal, a lake's classification may change because of changes in precipitation or in the water-distribution system. The Humboldt River area (*G*) is a terminal sink except for rare floods when flows terminate in an adjacent terminal sink. Alternatively, a lake may be flow-through under normal circumstances but become terminal during a drought.

In the Tulare Lake Bed Area (*Y*), drain water is managed as if the basin were terminal. Drain water from the area is not allowed to discharge to the San Joaquin River, rather the drain water is stored in terminal ponds where it is consumed by evaporation.

EFFECTS OF UPSTREAM SOURCES OF SELENIUM

If selenium is transported in the water used for irrigation into an area, selenium problems may occur in that area even without a local source of selenium. Sources of selenium can include irrigation drainage from upstream areas. For example, the Colorado River ultimately receives drainwater containing selenium from irrigation projects along the Green, San Juan, and Gunnison Rivers. The Colorado River thereby imports selenium into the Salton Sea area (*U*).

Other possible sources include natural drainage from seleniferous rocks or discharges from mining or oil-field operations. The Rio Grande passes over Upper Cretaceous and Tertiary marine sedimentary rocks and deposits hundreds of miles upstream from irrigated lands in the lower Rio Grande Valley near Brownsville, Texas. The Vermillion Creek Basin in Colorado and Wyoming is characterized by large expanses of unvegetated, highly erodible Mancos Shale, a seleniferous Upper Cretaceous marine sedimentary rock. Low-altitude spring runoff from this area provides a significant natural source of selenium in the middle Green River Basin (*N*; James Yahnke, Bureau of Reclamation, written commun., 1998). In Nevada, after it flows through spoils from an abandoned gold mine, a small creek has selenium concentrations in excess of 35 µg/L when the discharge is 1.5 ft^3/s (Independence Mining Company data on file at the U.S. Forest Service office in Elko, Nev.). Flow in the creek discharges to the North Fork Humboldt River, more than 200 mi upstream from where the water is used for irrigation in the Humboldt River area (*G*).

The significance of a single source of selenium in the budget of large rivers is illustrated by a sewage treatment plant in northern Utah. Seepage from the sewage lagoons for the town of Vernal passes through Mancos Shale and discharges to Ashley Creek, a tributary to the Green River. The seepage mobilizes large amounts of selenium. A sample of seepage downgradient from the sewage lagoons contained 16,000 µg/L of selenium (Stephens and others, 1992, p. 155). Leakage from the sewage lagoons is a principal source of selenium in the Ashley Creek Basin (Stephens and others, 1992). Seven measurements made during the reconnaissance and detailed investigations (Stephens and others, 1988; Peltz and Waddell, 1991) showed an average selenium load of about 7.5 lb/d from Ashley Creek where it discharges into the Green River. Almost 200 mi downstream, during 1985–94 , the mean selenium load for the Green River near the confluence with the Colorado River was 53.0 lb/d (Engberg, 1999). Thus, about 14 percent of the selenium load of the Green River could originate from a single site on a small stream.

TEMPORAL CHANGES IN SELENIUM CONCENTRATIONS

Selenium concentrations at a site can change from hour to hour, month to month, or year to year. All the samples from a few of the early reconnaissance investigations were collected during the middle of the irrigation season in a single year, and no information about temporal changes in contaminant concentrations was obtained. Later reconnaissance-level investigations, during which samples were collected throughout the entire irrigation season, provided information about seasonal changes in selenium concentrations. Only in the detailed investigations (table 1) were samples collected over a sufficiently long time and frequently enough to define monthly and annual changes in selenium concentrations.

Selenium concentrations at a site can show large changes during a year. The lowest selenium concentrations might be expected to occur always during the irrigation season, but this is not necessarily so. Selenium concentrations in water samples from Lake Creek of the Sun River area *(X)* vary seasonally (fig. 24*A*) and correlate negatively with discharge (fig. 24*B*). The highest concentrations during 1990–92 were in samples collected during the winter, whereas during 1993, the highest concentrations were in samples collected during the spring and summer. Flow in Lake Creek is a mixture of precipitation runoff and inflow of highly seleniferous seepage from nonirrigated lands in the basin and water pumped into Lake Creek from an adjacent basin. The pumped water consists of irrigation return flow, native flow, and runoff as well as seepage from nonirrigated lands. Thus, selenium concentration in Lake Creek at any time depends on the relative contribution of water from several sources within and outside the basin.

Samples of ground water from wells in the middle Green River Basin (*N*) also showed rapid seasonal changes (fig. 25). This effect was more pronounced in the shallow well, where selenium concentrations decreased from 410 to 7 µg/L during the 3.5 months of the 1988 irrigation season. Selenium concentrations returned to almost the original concentration by the beginning of the 1989 irrigation season.

Selenium concentrations can change greatly from one year to the next. Selenium concentrations in Rasmus Lee Lake, Wyo., during March–April in 1988 and 1989 are shown in figure 26. Selenium concentrations were nearly 10 times lower in 1989 than they had been in 1988. Large increases in precipitation also can result in nondetection of selenium in an area that normally would be expected to be contaminated. For example, selenium has been measured in surface- and ground-water samples from the Milk River Basin (*P*), an area of seleniferous sedimentary rocks, yet selenium was not detected in a single surface-water sample collected during the reconnaissance investigation of that area. Presser and others (1994) cited work by Everett Pitt of Northern Montana College (Havre, Mont.) in which he reported selenium concentrations of 70 to 100 µg/L in a creek in the Milk

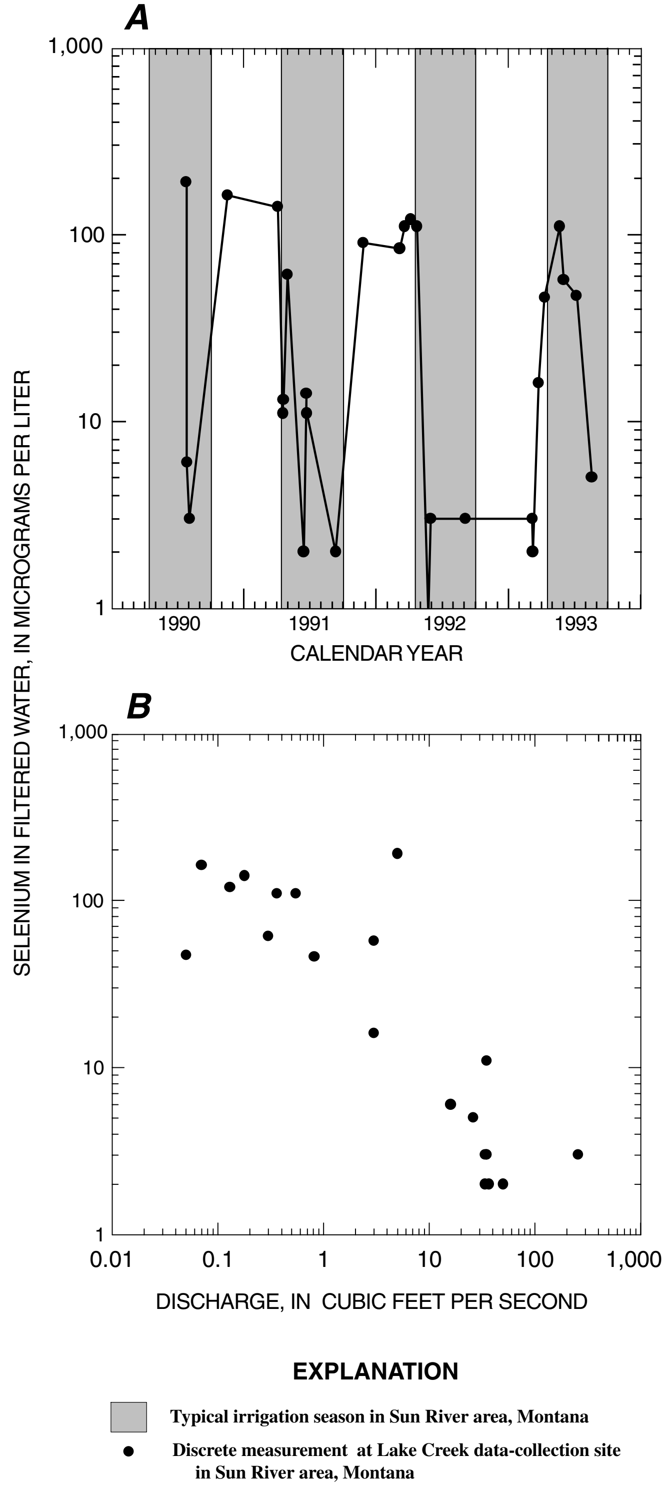


FIGURE 24. Selenium concentrations in surface water, Sun River area, Montana, 1990–93. *A*, Irrigation and nonirrigation seasons; calendar years are divided into months. *B*, Discharge at Lake Creek data-collection site near Power, Mont.

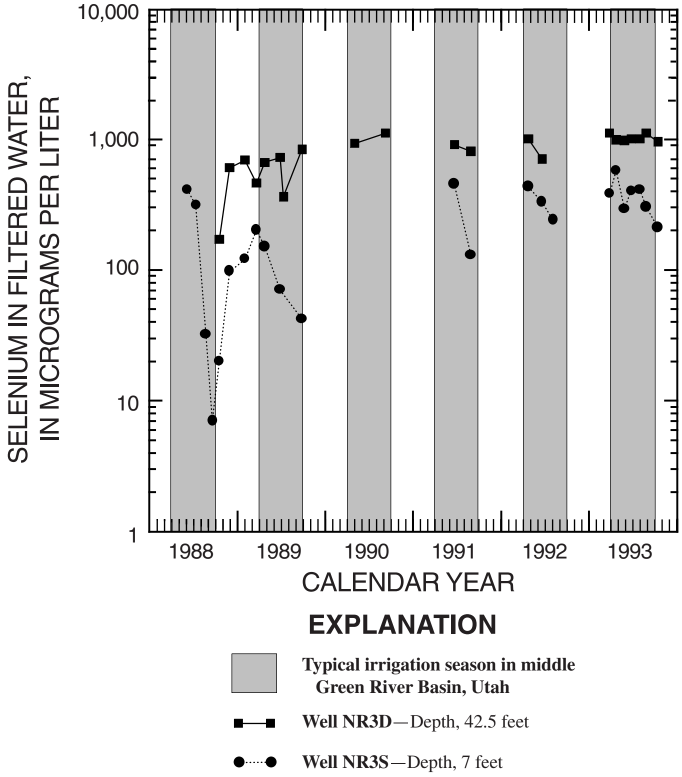


FIGURE 25. Seasonal changes in selenium concentrations in deep and shallow wells near North Roadside Pond, middle Green River Basin, Utah, 1988–93. Gaps in connecting lines indicate periods of no record.

River Basin. Lake Bowdoin in that basin had selenium concentrations of 6 μg/L in 1985, although when the NIWQP samples were collected in 1986 selenium concentrations were less than 1 μg/L (Lambing and others, 1988). Furthermore, many saline seeps that contain unusually high concentrations of trace elements, particularly selenium, were mapped in the Milk River Basin by Miller and Bergantino (1983). Although the distribution of fallowing dryland fields also temporarily affects selenium concentrations, the principal reason selenium was not detected in surface water during the Milk River Basin reconnaissance investigation is probably because of dilution during the period of sample collection. All the samples for the area were collected during June or August in a flood year when the annual rainfall was nearly twice the normal amount (table 17).

INTERRELATION OF GEOLOGY, CLIMATE, AND HYDROLOGY

Geologic units were compiled into three main groups based on the geologic map by King and Beikman (1974): (1) Upper Cretaceous stratified sedimentary sequences that were deposited mainly in marine environments [hereafter referred to as Upper Cretaceous marine sedimentary deposits or rocks]; (2) Paleocene to Pliocene mainly marine, stratified sedimentary sequences [hereafter referred to as Tertiary marine sedimentary deposits or rocks]; and (3) Paleocene to Pliocene continental sedimentary deposits [hereafter referred to as Tertiary continental sedimentary deposits or rocks].

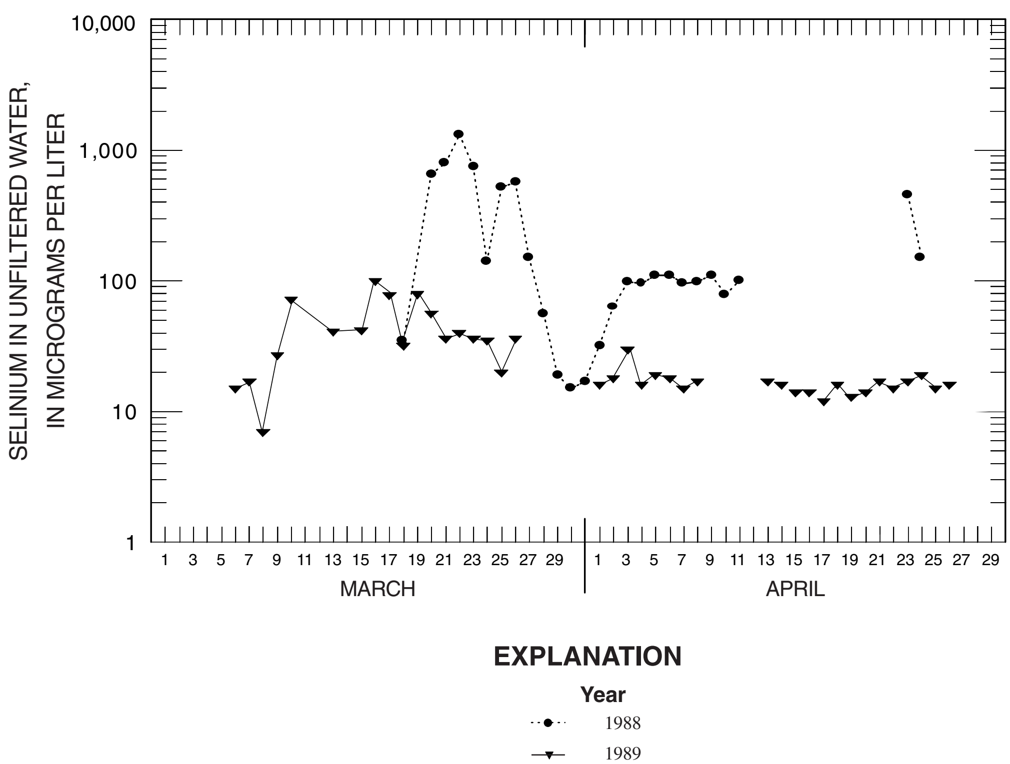


FIGURE 26. Selenium concentrations in Rasmus Lee Lake, Kendrick Reclamation Project, Wyoming, during March–April 1988 and March–April 1989. Gaps in connecting lines indicate periods of no record.

The 26 study areas were classified into groups primarily on the basis of their association or lack of association with Upper Cretaceous marine sedimentary rocks (table 18):

- areas not associated with Upper Cretaceous marine sedimentary rocks
- areas where the bedrock beneath irrigated land consists mainly of Upper Cretaceous marine sedimentary rocks
- areas where the bedrock beneath irrigated land is a combination of Upper Cretaceous marine sedimentary rocks and Tertiary continental sedimentary deposits
- areas where the bedrock in mountains upland from irrigated land includes Upper Cretaceous marine sedimentary rocks or includes both Upper Cretaceous and Tertiary marine sedimentary rocks
- areas where rivers upstream from irrigated land traverse Upper Cretaceous marine sedimentary rocks or Upper Cretaceous and Tertiary marine sedimentary rocks.

Upper Cretaceous marine sedimentary rocks were found to be either directly or indirectly associated with all 12 areas classified as selenium contaminated (table 18). Upper Cretaceous marine sedimentary rocks are of particular importance because these rocks generally are seleniferous and because they are common in the NIWQP study areas. Eight study areas have no direct or indirect association with Upper Cretaceous marine sedimentary rocks and none of them were classified as seleniferous or selenium contaminated.

NIWQP study areas containing Tertiary continental sedimentary deposits were not classified separately because, in all but two areas, they also are associated with Upper Cretaceous marine sedimentary rocks. Tertiary marine sedimentary deposits, although known to be important sources of selenium in the San Joaquin Valley in California, were not assigned to a separate group because of their minor importance in the NIWQP data set.

The climate of the study areas was represented by the mean annual precipitation and the EI (table 18). For the Milk River Basin (*P*) and the Riverton Reclamation Project (*S*), the precipitation during the year of data collection was substantially different from the mean annual precipitation. All data for the Milk River Basin reconnaissance investigation was collected in June or August 1986, a year in which there was almost twice the normal amount of precipitation (table 17). Much more water than normal also was delivered to the area in the months prior to data collection. Selenium was not detected in any surface-water samples from the basin owing to dilution from above-normal precipitation. Because of the unusual amount of dilution that year, the precipitation for the year of data collection was used for data analysis and calculation of the evaporation index instead of the mean annual precipitation in the Milk River Basin.

In the Riverton Reclamation Project (*S*), precipitation during the year of data collection was less than half the normal amount (table 17). However, because stored water was available in the months prior to data collection, more water than normal was delivered to the area to offset the effects of drought. Because less-than-average precipitation did not reduce the amount of water delivered to the Riverton Reclamation Project, the average precipitation was used to calculate the evaporation index.

The hydrology of the study areas was characterized by the presence of upstream selenium sources or by the presence of terminal lakes or ponds in the area (table 18).

The relation between selenium concentrations in surface water and two measures of aridity in study areas where irrigated lands overlie Upper Cretaceous marine sedimentary bedrock is shown in figure 27*A,B*. The upward trend in selenium concentration correlates with increasing aridity. Data from the Kendrick Reclamation Project (*H*) and San Juan River area (*V*) were not used in the statistical analysis of the relation between selenium and the climatic variables because of known sample bias (discussed in section "Statistical Bias," p. 18). Because all selenium values for surface-water samples from the Milk River Basin (*P*) were less than the detection limit, data from that area also were excluded.

As Barnes (1985) suggested, in areas where marine sedimentary rocks comprise the bedrock, annual precipitation between 12 and 20 in. separates seleniferous from nonseleniferous areas. To test the predictive capability of a statistically significant regression between the logarithms of annual precipitation and selenium concentration (adjusted $r^2 = 0.83$, $p < 0.001$), it was recomputed by using only data from areas where the precipitation was between 12 and 20 in. The relation was not significant (adjusted $r^2 = 0.06$, $p > 0.29$) when outliers for areas *F* and *N* were removed.

The statistically significant relation between the logarithms of EI and selenium concentration (adjusted $r^2 = 0.70$, $p = 0.003$) is still evident even when outliers *F* and *N* are removed (adjusted $r^2 = 0.26$, $p = 0.14$). For EI, 26 percent of the variance is explained when the outliers are removed, but the percentage is even lower for precipitation, at 6 percent of the variance explained after outliers are removed. For this reason, EI rather than precipitation was chosen as the variable to represent climate.

For the study areas where irrigated lands overlie Upper Cretaceous sedimentary bedrock, a regression on the data in figure 27*B* was used to identify what the EI would be if the 75th percentile of the selenium concentrations exceeds the chronic criterion. Excluding data from two areas (*H* and *V*) because of sample bias and one area (*P*) because of non-detects, the regression indicated that when the 75th percentile exceeded 3 µg/L, the EI was about 2.5 and when it exceeded 5 µg/L, the EI was about 3.0.

TABLE 18. *Summary description of degree of selenium contamination and physical characteristics of National Irrigation Water Quality Program study areas*

[Abbreviation and symbols: µg/L, micrograms per liter; —, no data; <, less than]

Study area		Selenium seventy-fifth-percentile concentration[2] (µg/L)	Study-area classification[3]	Geology[4]	Climate		Hydrology	
Identifier[1]	Name				Mean annual precipitation (inches)	Evaporation index[5]	Maximum selenium concentration in source water[6] (µg/L)	Terminal lakes or ponds during nonflood years
A	American Falls Reservoir, Idaho	1.0	UC	Irrigated lands not associated with uKm	10.9	3.7	—	No
B	Angostura Reclamation Unit, South Dakota	4.5	S	Irrigated lands underlain by uKm	16.4	2.8	2	Yes
C	Belle Fourche Reclamation Project, South Dakota	5	C	Irrigated lands underlain by uKm	14.4	2.8	3	Yes
D	Columbia River Basin, Washington	<1	UC	Irrigated lands not associated with uKm	8	5.0	<1	Yes
E	Dolores–Ute Mountain area, Colorado	7.0	C	Irrigated lands underlain by uKm	12	4.4	<1	No
F	Gunnison River Basin–Grand Valley Project, Colorado	35	C	Irrigated lands underlain by uKm	10	5.0	9	No
G	Humboldt River area, Nevada	2.0	UC	Irrigated lands not associated with uKm	5.5	8.1	1	Yes
H	Kendrick Reclamation Project, Wyoming	64	C	Irrigated lands underlain by uKm	12	3.7	2	Yes
I	Klamath Basin Refuge Complex, California–Oregon	<1	UC	Irrigated lands not associated with uKm	13	3.0	<1	Yes
J	Lower Colorado River valley, California–Arizona	2.0	UC	Rivers traverse uKm upstream from irrigated land.	4.5	18.9	2	Yes
K	Lower Rio Grande valley, Texas	1.0	UC	Rivers traverse uKm and Tm upstream from irrigated land.	25.9	2.2	1	No
L	Malheur National Wildlife Refuge, Oregon	<1	UC	Irrigated lands not associated with uKm	10	4.3	<1	Yes
M	Middle Arkansas River Basin, Colorado–Kansas	10	C	Irrigated lands underlain by uKm and Tc	14.6	4.0	5	No
N	Middle Green River Basin, Utah	73	C	Irrigated lands underlain by uKm and Tc	7.6	5.7	—	Yes
O	Middle Rio Grande, New Mexico	<1	UC	Irrigated lands underlain by Tc, not associated with uKm.	9.4	6.8	<1	Yes
P	Milk River Basin, Montana	<1	UC	Irrigated lands underlain by uKm	[7]21.4	[7]1.9	<1	Yes
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	2.0	UC	Irrigated lands not associated with uKm	9.5	4.5	<1	No
R	Pine River area, Colorado	6.0	C	Irrigated lands underlain by uKm and Tc	14	3.5	<1	No
S	Riverton Reclamation Project, Wyoming	5.0	C	Bedrock includes uKm in mountains upland from irrigated lands underlain by Tc	8.1	4.9	<1	No
T	Sacramento Refuge Complex, California	<1	UC	Bedrock includes uKm in mountains upland from irrigated land	18.5	2.6	<1	No
U	Salton Sea area, California	8.0	C	Rivers traverse uKm, upstream from irrigated land	3	24.5	3	Yes
V	San Juan River area, New Mexico	3.0	S	Irrigated lands underlain by uKm and Tc	7.6	7.4	<1	Yes
W	Stillwater Wildlife Management Area, Nevada	<1	UC	Irrigated lands not associated with uKm	5.3	10.0	<1	Yes
X	Sun River area, Montana	7.5	C	Irrigated lands underlain by uKm	12	3.0	<1	Yes
Y	Tulare Lake Bed area, California	265	C	Bedrock includes uKm and Tm in mountains upland from irrigated land	5.5	11.2	—	Yes
Z	Vermejo Project area, New Mexico	6.0	C	Irrigated lands underlain by uKm	13.8	3.9	1	Yes

[1] Used in figure 2 to show locations of study areas.
[2] Analyses of filtered surface-water samples collected from study area in and downstream from irrigated lands.
[3] C, contaminated (75th percentile of selenium concentrations equals or exceeds 5 micrograms per liter). S, seleniferous (75th percentile of selenium concentrations equals or exceeds 3 but is less than 5 micrograms per liter). UC, uncontaminated (75th percentile of selenium concentrations is less than 3 micrograms per liter). See section "Selenium Concentration," p. 49.
[4] After King and Beikman (1974): Tc, mainly Tertiary continental sedimentary deposits; Tm, Tertiary marine sedimentary deposits; uKm, mainly Upper Cretaceous marine sedimentary rocks.
[5] Mean annual free-water-surface evaporation divided by mean annual precipitation.
[6] Water body identified as providing water used for irrigation.
[7] Calculated using precipitation during year of data collection rather than mean annual precipitation.

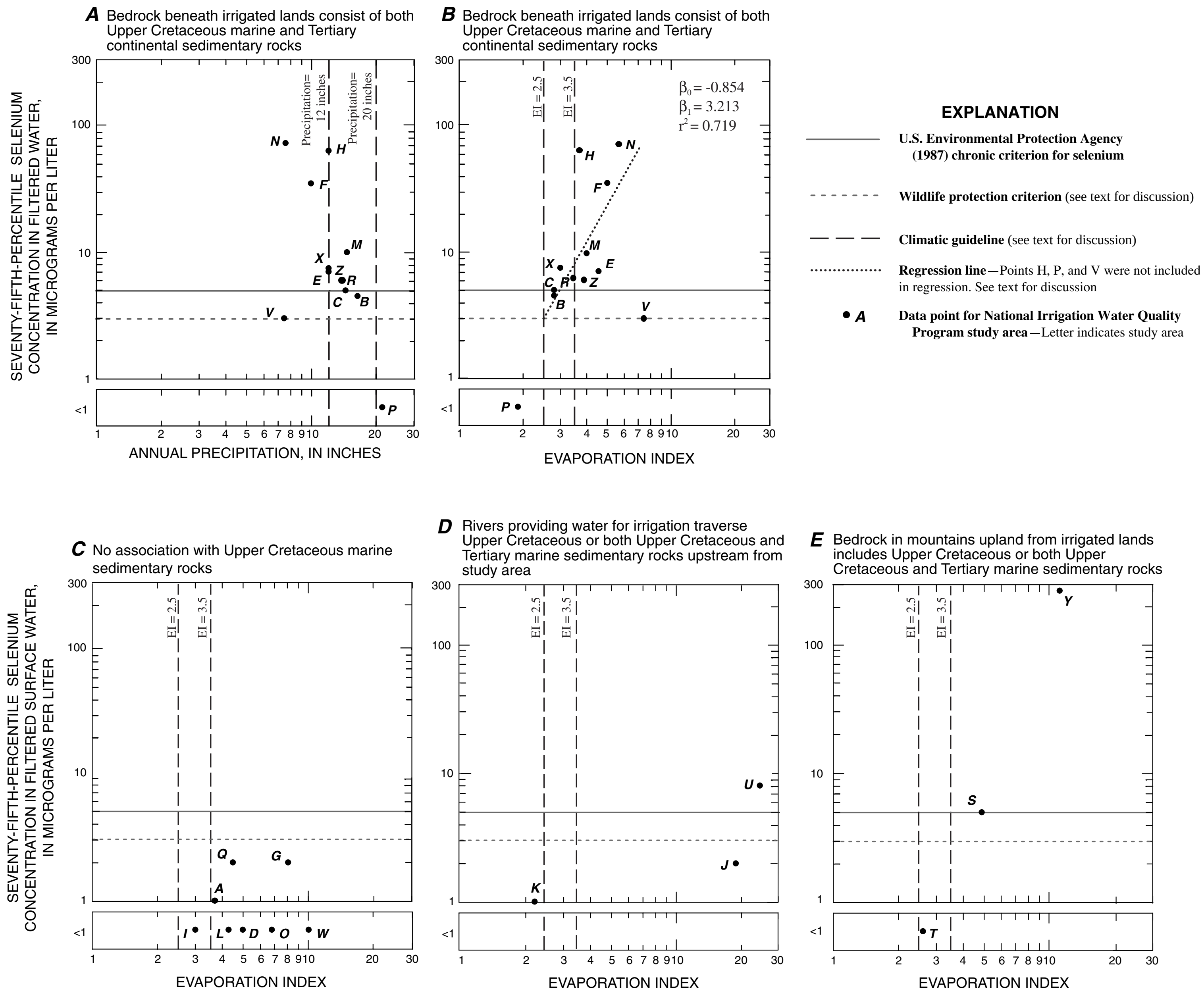


FIGURE 27. Relations between selenium concentrations, climate data, and geology for 26 National Irrigation Water Quality Program study areas.

Where there is no association with Upper Cretaceous marine sedimentary rocks, increasing aridity was not associated with increases in selenium concentration (fig. 27C), and the 75th percentile of the selenium concentrations did not exceed the USEPA chronic criterion of 5 µg/L. In areas where selenium is imported into the area in irrigation water after passing over Upper Cretaceous or Tertiary marine sedimentary deposits upstream (J, K, and U), or areas where Upper Cretaceous or Tertiary marine sedimentary deposits are exposed upland from irrigated lands (S, T, and Y), the 75th percentile of the selenium concentrations can exceed the USEPA chronic criterion in arid environments (fig. 27*D,E*).

SELENIUM IN BIOTA

EFFECTS OF SELENIUM ON ANIMALS

In vertebrates, selenium is a required micronutrient and is an essential part of several enzymes (for example, cellular glutathione peroxidase) and other proteins having unknown functions (Maas, 1998). Selenium is an important antioxidant, which helps to explain its role in preventing a number of diseases. In humans, selenium deficiency is a major factor in Keshan disease, which causes congestive heart failure in infants and young children. The disease was endemic in certain regions of China but has been eliminated almost entirely by supplying sodium selenite pills to those at risk (Maas, 1998).

Selenium is unusual among the required micronutrients in that toxic amounts are not substantially greater than required amounts. For example, it is required as a nutrient in the diet of fish at concentrations of about 0.1 to 0.5 µg/g but becomes toxic at concentrations greater than 3 µg/g (Lemly, 1998). In the 1930's, poisoning of livestock in the north-central United States was related to consuming seleniferous forage. Chronic selenosis in cattle and horses (alkali disease) involves loss of hair in the mane and tail and distinctive cracks in the hooves that can cause lameness (O'Toole and Raisbeck, 1998).

In birds, the embryo is the life stage most sensitive to selenium poisoning (Heinz, 1996). Selenium poisoning leads to the development of deformed chicks that cannot hatch. The principal deformity of embryos of mallard dams exposed to selenium was arrested development of the lower beak and spoonbill narrowing with lateral deviation of the upper beak (O'Toole and Raisbeck, 1998). In fish, the most sensitive stage is the larval stage (Lemly, 1998), and deformities occur as the larval fish use the selenium-contaminated yolk sac (Lemly, 1998). Typical deformities in fish include abnormal curvature of the spine, deformed or missing fins and eyes, and deformed mouths.

Sublethal selenium poisoning of adult birds causes cachexia (weight loss in the presence of adequate nutrition) and lethargy (Ohlendorf and others, 1988; Albers and others, 1996). The unhealthy birds are more susceptible to predation and are less able to make long migrations, establish nests, and raise chicks. General debility and poor body weight caused by selenium was believed to be the reason coots failed to nest at Kesterson in 1984 and 1985 (Ohlendorf and others, 1988); their body weight averaged 25 percent below normal regardless of whether they were found dead or still alive and active.

SELENIUM GUIDELINES

Selenium concentrations in biological material were compared to concentrations (table 19) that have been demonstrated to have adverse effects on the species itself or on a similar species (an *effect* level) or that can have adverse effects on another species if it is consumed (a *dietary effect* level). For plants and invertebrates, selenium concentrations are compared only to the dietary effect level of 3 µg/g. Hilton and others (1980), Hamilton and others (1990), Hamilton and others (1996), and

TABLE 19. *Selenium concentrations in biota that may adversely affect sensitive fish or aquatic birds*

[Abbreviation and symbol: µg/g, micrograms per gram; —, no data]

Tissue	Effect level[1] (µg/g, dry weight)	Dietary effect level[2] (µg/g, dry weight)
Plants	—	3
Invertebrates	—	3
Whole fish	[3]4–6	3
Birds:		
Liver	[4]30	—
[5]Egg		
High risk	[6]12.5	—
Threshold	[7]6	—

[1] Concentrations known to have adverse effects on a species.

[2] Selenium concentration in an organism that can have adverse effects on another species if consumed. Lemly (1996c) identified 3 micrograms per gram as toxic threshold concentration for selenium in aquatic food-chain organisms consumed by fish and wildlife.

[3] Lemly (1996c) identified 4 micrograms per gram as threshold concentration that affects health and reproductive success of freshwater and anadromous fish. U.S. Department of the Interior (1998) estimated that 4 to 6 micrograms per gram was threshold range for reproductive failure in sensitive species such as bluegill.

[4] U.S. Department of the Interior (1998) concluded that liver concentrations greater than 30 micrograms per gram are very likely to be associated with reproductive impairment.

[5] The effect levels used for both individual eggs and egg sets are the same. See text for discussion.

[6] CH2M Hill (2002) identified 12.5 µg/g as the concentration at which 10 percent of mallard eggs became inviable. See text for discussion.

[7] Six micrograms per gram is a threshold concentration for increased risk of egg inviability. Skorupa (1998, 1999) identified the upper boundary of safe exposure levels for stilt eggs as approximately 6 micrograms per gram. CH2M Hill (2002) identified 6.4 µg/g as the lower 95 percent confidence interval for the EC_{10} in mallard eggs. See text for discussion.

Lemly (1996c, p. 435) identified a toxic threshold of about 3 µg/g for selenium in aquatic food-chain organisms consumed by fish and wildlife. DeForest and others (1999) proposed a higher threshold value of about 10 µg/g for warmwater food chains. Hamilton (in press) supports continued use of the 3 ug/g threshold value, however, and argues that DeForest and others (1999) reached their conclusion based on an incomplete review of the scientific literature. In selenium-normal (uncontaminated) environments where waterborne selenium is less than 1 µg/L, selenium concentrations in freshwater algae typically range from 0.1 to 1.5 µg/g and in freshwater macrophytes, typically range from 0.1 to 2.0 µg/g (U.S. Department of the Interior, 1998). Background selenium concentrations in aquatic invertebrates range from 0.4 to 4.5 µg/g and typically are less than 2 µg/g (U.S. Department of the Interior, 1998).

The selenium concentration at which fish become toxic to predators that consume them is near the level at which selenium begins to have reproductive effects in the fish themselves. Selenium concentrations in whole-body fish samples are compared to dietary effect levels (3 µg/g) and to concentrations associated with adverse biological effects on the fish themselves. Selenium concentrations in whole-body fish samples from selenium-normal environments range from < 1 to 4 µg/g and are typically <2 µg/g (U.S. Department of the Interior, 1998). Selenium concentrations in gravid females of 4 to 6 µg/g, only slightly greater than the normal range, can affect reproduction of sensitive fish species through transfer of the selenium from the parent to the egg (U.S. Department of the Interior, 1998). Transfer of selenium to the developing fish embryo during yolk-sac absorption can cause death of the fry within a few days after hatching (Lemly, 1996c).

Selenium concentrations in bird-liver tissue from selenium-normal environments are typically less than 10 µg/g (U.S. Department of the Interior, 1998). Selenium concentrations can be much higher in mercury-contaminated environments because selenium protects against mercury poisoning and therefore mercury-challenged organisms accumulate more selenium than normal. In mercury-normal environments, selenium concentrations greater than 30 µg/g are likely to be associated with reproductive impairment (U.S. Department of the Interior, 1998).

Selenium concentrations in eggs from selenium-normal environments commonly average less than 3 µg/g and the maximum concentrations are usually less than 5 µg/g (U.S. Department of the Interior, 1998). The threshold guideline for selenium-induced embryotoxic risk used in this report is 6 µg/g egg selenium (dry weight). The choice of this guideline is based on the findings from large-sample field studies of black-necked stilts reported by Skorupa (1998, 1999). Skorupa (1999) reported that this number was an estimate of the EC_{03} (3 percent effects concentration) for individual-level emryotoxicity. In other words, any individual egg with 6 or more µg/g selenium would have a 3 percent or greater chance of being inviable. This is viewed as the best existing estimate of the true threshold separating no effects concentrations from the lowest detectable effect concentration.

Recently, Fairbrother and others (1999) reviewed laboratory data for mallard ducks and estimated that the EC_{10} for selenium embryotoxic effects was 16 µg/g. That analysis was extended by CH2M Hill (2002) and resulted in an estimate of 12.5 µg/g egg selenium for the EC_{10} with 95 percent confidence boundaries of 6.4 to 16.5 µg/g. The lower end of the 95-pecent confidence limit is comparable to the 6 µg/g guideline used in this report. CH2M HILL's (2002) EC_{10} estimate of 12.5 µg/g egg selenium is used in this report as guideline for high-risk selenium-exposure. In practice, however, none of the applicable Federal wildlife laws (such as the Migratory Bird Treaty Act or Endangered Species Act) allow *any* foreseeable, human-caused mortality of protected populations, let alone 10 percent mortality. Therefore, the value of 6 µg/g is used in this report as the primary guideline for evaluating selenium concentrations in eggs.

Selenium concentrations in bird eggs are compared to applicable criteria in two ways—as individual eggs and as sets of eggs representing a distinct breeding population of birds. Population-level thresholds are commonly lower than individual-level thresholds because they are based on population averages even though the maximum values determine when hens in the population begin to show a toxic response (U.S. Department of the Interior, 1998). However, the 6 µg/g guideline is used for both purposes in this report to avoid confusion regarding individual versus population levels of analysis. For sets of avian eggs it is not uncommon for the maximum individual value in the set to be at least twice the mean. In the NIWQP data set the maximum was at least twice the mean in twenty percent of the eggsets that contained 10 or more individual eggs. Therefore, when the population mean exceeds the guideline of 6 µg/g egg selenium there is a high probability that some eggs in that population will exceed 12.5 µg/g.

SUMMARY STATISTICS AND COMPARISON WITH GUIDELINES

Summary statistics were computed for selenium concentrations in plant, invertebrate, fish, and bird tissues (table 20) and were compared to effect levels. The categories used to group species are broad. Thus, the plant category groups together samples from algae, pondweed, and cattail roots, and the invertebrates category groups clams, insects, and crayfish. However, only whole-body fish samples are included in the fish category; fish-tissue samples from many study areas included fillets (and rarely gonads), but these tissues were not compared to the guidelines.

Plant and animal tissues are clearly different in the percentage of samples where selenium was detected. Only 79 percent of the plant samples contained selenium concentrations greater than the reporting limit. This may be because, except for some hyperaccumulating plants, selenium is not a required micronutrient for higher plants. Selenium was detected in 92 percent of the invertebrate samples and in more than 99 percent of the samples from fish and birds. Because selenium is a required micronutrient for animals, selenium is expected to be found in most animal tissues.

Twenty-five percent of the plant samples had selenium concentrations exceeding the dietary effect level, whereas 57 percent of the invertebrate samples and 61 percent of the fish samples exceeded it (table 20). These data suggest species whose food chains are based on invertebrates and fish may be at greater risk than species whose food chains are based on plants. Exceptions to this generalization may occur; DuBowy (1989) found that, sometimes, due to the low caloric content of plants, herbivorous marsh birds must consume so much mass that they get a higher dietary dose of selenium than insectivorous marsh birds feeding on a lower mass of calorically rich, but more contaminated, insects.

About 44 percent of the bird-egg samples exceeded the threshold effect level of 6 µg/g for individual eggs, and about 16 percent of the bird-liver samples exceeded the effect level of 30 µg/g. Elevated concentrations of selenium in the liver should be taken only as an indication that further study is warranted (U.S. Department of the Interior, 1998).

NATIONAL IRRIGATION WATER QUALITY PROGRAM STUDY-AREA COMPARISONS

Box plots for selenium concentrations in plant, invertebrate, fish, and bird tissues in the 26 areas are shown in figure 28. Effect levels for selenium toxicity are shown in the figure, but effect levels for selenium deficiency are not shown. Because selenium is a required mineral nutrient in animals, adverse effects from selenium deficiency also can occur.

SAMPLE BIAS

The exceedance data (table 20) are strongly affected by sample bias because samples were collected preferentially from the detailed study areas, which were typically selected for additional study because of selenium contamination. Therefore, the 44-percent exceedance value for bird eggs (table 20), for example, cannot be extrapolated to mean that 44 percent of the bird eggs in the Western United States contain potentially toxic amounts of selenium. Of the 497 eggs that contained selenium concentrations exceeding the high-risk level of 12.5 µg/g, almost 79 percent were from the Kendrick Reclamation Project (*H*) and the middle Green River Basin (*N*).

Another type of bias, called survivor bias, can skew the results of tissue studies toward lower contaminant concentrations because animals having high contaminant loads are less likely to be sampled than animals with low contaminant loads. Methods for collecting free-ranging fish and birds typically gather only specimens that were alive at the time of collection. Therefore, only the population of survivors is being sampled.

TABLE 20. *Summary statistics for selenium in plants, invertebrates, fish, and bird livers and eggs from National Irrigation Water Quality Program study areas*

[Abbreviation and symbol: µg/g, micrograms per gram; —, no data]

Category of biota 1 2 3 4 5	Summary statistics				Exceedance (percent)	
	Median (µg/g, dry weight)	Interquartile range (µg/g, dry weight)	Number of samples	Detects (percent)	Dietary effect	Effect
Plants	1.0	2.7	1,086	79.3	[1]25.0	—
Invertebrates	3.4	6.2	751	92.0	[1]57.1	—
Whole fish	3.9	5.1	2,177	99.6	[1]61.3	[2]32.4
Birds:						
Liver	10	16.1	[3]1,234	99.8	—	[4]15.7
Egg	5.2	9.2	2,055	99.5	—	[5]44.1/24.2
Egg sets	4.3	6.1	517	--	--	[5]37.1/13.3

[1] Relative to dietary effect level of 3 micrograms per gram.

[2] Relative to effect level of 6 micrograms per gram.

[3] Eighty tissue samples in the database are a combination of liver and kidney tissue. They were not used in this summary because effect levels have not been established for that combination of tissues.

[4] Relative to effect level of 30 micrograms per gram.

[5] The first value is relative to threshold level of 6 micrograms per gram. The second value is relative to the high-risk level of 12.5 micrograms per gram.

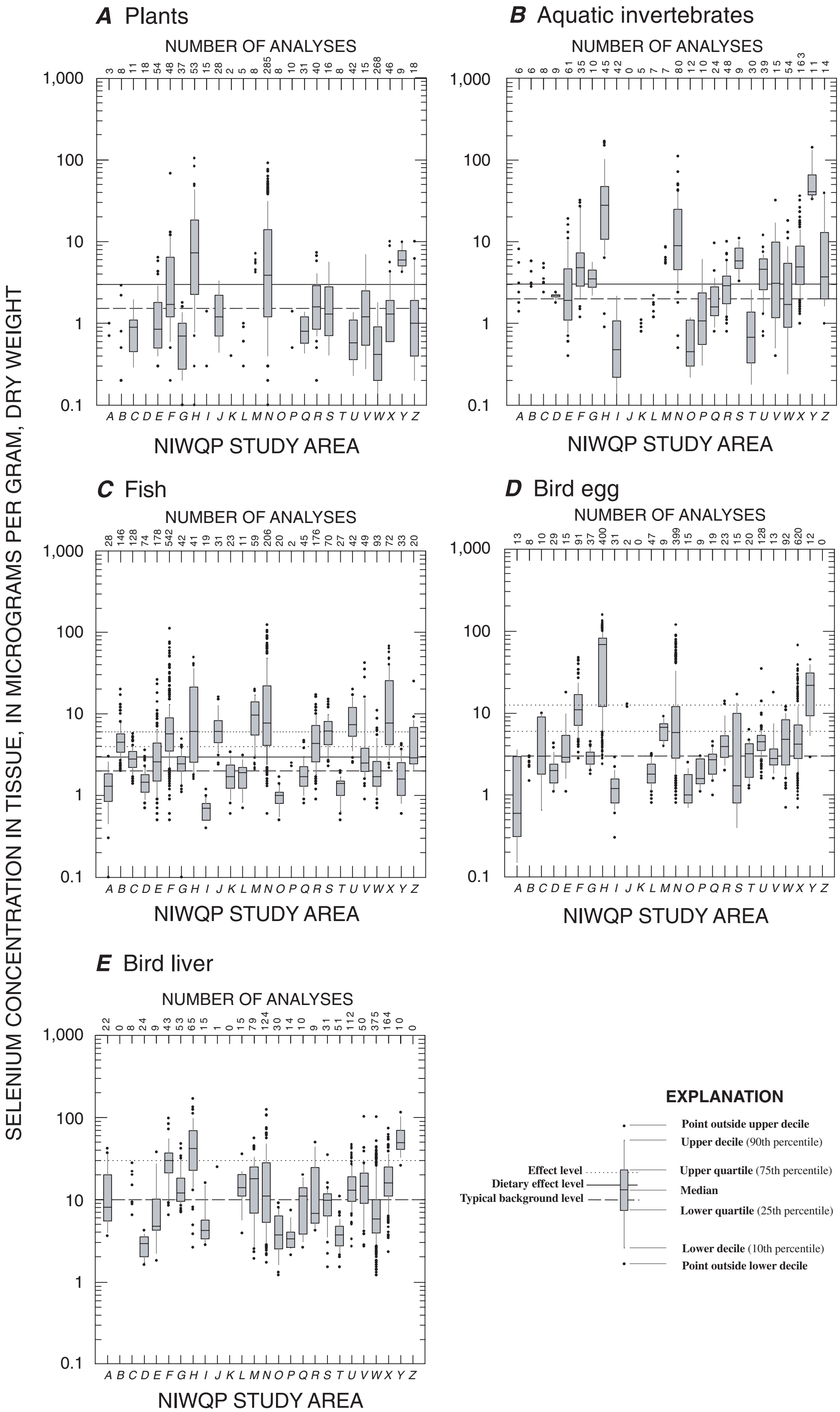


FIGURE 28. Selenium concentrations in plants, aquatic invertebrates, fish, and birds (livers and eggs) in National Irrigation Water Quality Program (NIWQP) study areas. Typical background level (upper limit) of selenium concentrations from U.S. Department of the Interior (1998). Some NIWQP areas either show no plotted data because data were below reporting limit or were not plotted because no analyses of the given type were done.

This can be an important issue with regard to assessing effects of selenium exposure because individual and taxonomic sensitivity to selenium is quite variable (Lemly, 1993c; Albers and others, 1996; Green and Albers, 1997; O'Toole and Raisbeck, 1998; Skorupa, 1998). Furthermore, survivors can be devoid of the histologic lesions typical of fatally poisoned individuals even when survivors possess the same level of tissue selenium that proved fatal to more-sensitive individuals (Albers and others, 1996). Thus, survivor bias can skew risk assessments because of falsely concluding that a given level of exposure is insufficient to induce toxicity (as evident in histologic lesions) or because of underestimating levels of a population's exposure to selenium.

As a hypothetical example of underestimating levels of exposure because of survivor bias, suppose that the probability-density function for exposure of a population of animals was uniform across a range of 0 to 100 µg/g selenium in tissue and that selenium-induced mortality increased by 20-percent increments with every 20-µg/g increase in selenium in tissue. For this hypothetical situation, a population having an actual mean exposure of 50 µg/g tissue selenium would be assessed as having a mean exposure of only 22 µg/g selenium in tissue on the basis of sampling only the survivors—a negative bias of more than 50 percent. Clearly, as the mortality-response function steepens, sampling highly exposed survivors becomes less likely and exposure surveys become more skewed. An important aspect of survivor bias is that it always affects estimates of toxic sensitivity and estimates of population exposure in the same direction: Because both sensitivity and exposure are underestimated, the overall bias toward underestimating true risk is compounded.

PLANTS

As primary producers, aquatic plants are important sources of food for higher trophic-level organisms. Most plant samples had selenium concentrations less than the dietary effect level of 3 µg/g (fig. 28*A;* table 20), and the median concentration for most of the areas was less than 1.5 µg/g, the concentration typical of selenium-normal environments. In 4 of the 26 study areas (*F, H, M,* and *N*); however, more than 25 percent of the samples exceeded the dietary effect level and in 3 of these areas (*H*, *M*, and *N*), more than half exceeded it. The two areas having the highest median selenium concentrations in plant tissue were the Kendrick Reclamation Project (*H*) and the middle Green River Basin (*N*).

AQUATIC INVERTEBRATES

Aquatic invertebrates are a large component of the diet of some fish and birds. Only one terrestrial-invertebrate sample (earthworms) was collected; that sample was not included in the statistical analysis that follows. In 9 of the 25 study areas analyzed, the median selenium concentration in aquatic invertebrate tissue was less than 2 µg/g, which is typical of selenium-normal environments (fig. 28*B*). In 17 areas, more than one-quarter of the samples exceeded the dietary effect level, and in 13 of these 17 areas, more than one-half exceeded it. The three areas having the highest median selenium concentrations in invertebrate tissue were the Kendrick Reclamation Project (*H*), middle Green River Basin (*N*), and Tulare Lake Bed area (*Y*).

FISH

In 10 of the 26 study areas, the median selenium concentration in whole-body fish tissue was less than 2 µg/g, which is typical of selenium-normal environments (fig. 28*C*), and in five areas it was above background but less than the dietary effect level. In 14 areas, at least some fish samples exceeded the effect level of 6 µg/g, and in 7 areas, the median selenium concentration equaled or exceeded the effect level. The areas having the highest median selenium concentrations in fish tissue were the middle Arkansas River Basin (*M*), middle Green River Basin (*N*), Salton Sea area (*U*), and Sun River area (*X*). In three areas (*F, N,* and *X*), several samples were collected that had selenium concentrations that were ten times greater than the effect level.

BIRDS

In the NIWQP studies, selenium concentrations were measured in bird eggs (fig. 28*D*) or in adult or juvenile bird-liver tissue (fig. 28*E*). In two of the areas [middle Rio Grande (O) and San Juan River (V)] a combination of liver and kidney tissue were collected. For several reasons, bird-liver tissue is not optimum for determining whether selenium has adverse effects on the birds of an area: If adult birds are sampled, additional evidence is needed to prove that the birds did not just arrive from another area and bring the selenium with them. In adults, selenium poisoning has nonspecific effects such as emaciation, which makes determining the effect level for selenium from liver concentrations difficult (Heinz and others, 1988). Also, in contaminated areas, survivor bias can be a problem. Further, selenium concentrations in liver tissue can be elevated in selenium-normal environments that are contaminated by mercury (U.S. Department of the Interior, 1998). Selenium concentrations in liver tissue are more reliable for identifying populations that are not at risk from selenium toxicity than they are for identifying poisoned populations (U.S. Department of the Interior, 1998).

LIVER

Selenium concentrations in liver tissue typically show a wide range of concentrations, even in uncontaminated areas. In selenium-normal environments, the selenium concentration in liver is typically less than 10 µg/g but can be much higher in mercury-contaminated environments (U.S. Department of the Interior, 1998). In the American Falls Reservoir (*A*), Malheur National Wildlife Refuge (*L*), and Owyhee–Vale Reclamation

Project areas (*Q*), all of which were rated uncontaminated on the basis of selenium concentrations in surface water (table 15), selenium concentrations in liver show almost an order of magnitude range. In 3 of the 22 study areas analyzed, none of the selenium concentrations in liver-tissue samples exceeded the background concentration (fig. 28*E*); the median selenium concentration in 10 areas were within background levels; and the median concentration in all but 3 areas was less than the effect level. Even within the areas considered to be the most contaminated on the basis of selenium concentrations in surface water, some tissue samples were within the range of selenium concentrations found in tissue samples from uncontaminated areas. The three study areas having median selenium concentrations that equaled or exceeded the effect level (30 μg/g) were the Gunnison River Basin–Grand Valley Project (*F*), Kendrick Reclamation Project (*H*), and Tulare Lake Bed area (*Y*). Although the median selenium concentration in the Middle Green River Basin (*N*) only slightly exceeded background levels, almost 25 percent of the samples exceeded the effect level.

EGGS

Under NIWQP, more than 2,000 bird eggs were analyzed for contaminant concentrations. Sampling plans at many NIWQP study areas intentionally focused on the collection of bird eggs because earlier studies at Kesterson National Wildlife Refuge demonstrated the importance of evaluating embryo viability and the presence of terata. In 12 study areas, the median selenium concentration was within the background range (≤3 μg/g), and in almost all study areas, individual eggs were within this range (fig. 28*D*). In 15 of the 26 study areas, some eggs equaled or exceeded the 6 μg/g threshold effect level and in 11 areas some eggs equaled or exceeded the 12.5-μg/g high-risk effect level. In the Gunnison River Basin–Grand Valley Project (*F*), Kendrick Reclamation Project (*H*), Middle Green River Basin (*N*), and Tulare Lake Bed area (*Y*), 20 percent or more of the selenium concentrations exceeded the 12.5-μg/g high-risk effect level. Bird embryos having deformities typical of selenium poisoning were discovered in all four of these areas.

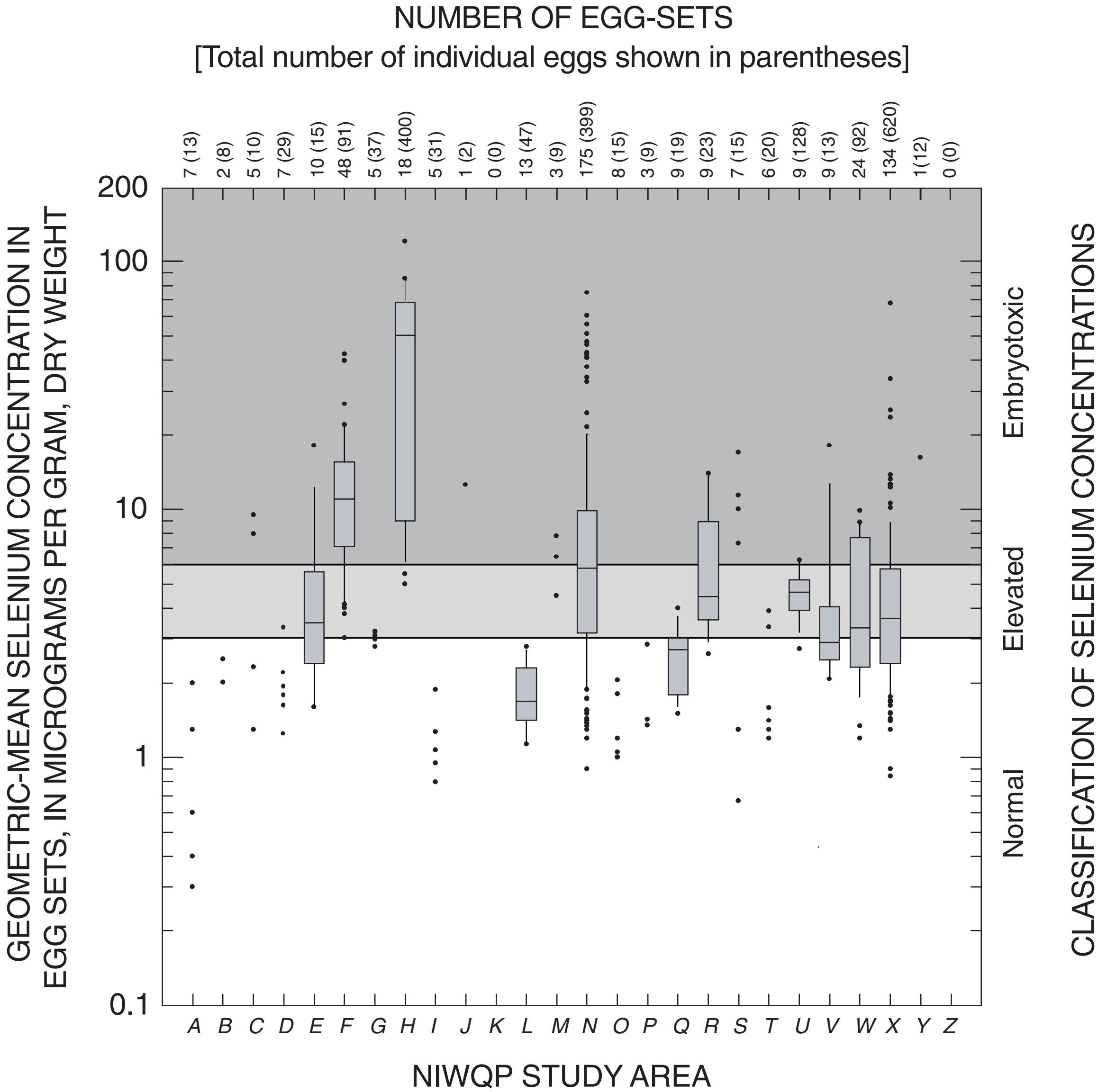
Reduced hatchability of bird eggs is an example of harm to wildlife populations that can be related statistically to the chemical content of the eggs. To analyze the data at the population level, eggs are grouped into sets and the geometric-mean selenium concentration for each set is calculated. A set is a species–site–year permutation that conceptually represents the eggs from a distinct breeding population of birds. For example, the 16 American avocet eggs that were collected in 1988 in the Kendrick Reclamation Project (*H*) at the Rasmus Lee Lake site represent a set; the 86 American avocet eggs that were collected at the same site in 1989 represent another set of eggs. In some cases, a single egg or composite sample represents the set for a particular breeding population of birds.

Box plots were prepared for geometric-mean selenium concentrations in sets of bird eggs in the study areas (fig. 29). Ranges of selenium concentrations in bird eggs that might be found in selenium-deficient areas are not shown in figure 29. In 6 of the 24 areas where bird eggs were collected, all geometric-mean selenium concentrations for egg sets were less than 3 μg/g, which is the expected concentration in selenium-normal environments; in 9 areas, most of the geometric-mean selenium concentrations were less than 3 μg/g (fig. 29). Fifty-five percent of the egg sets in the Kendrick Reclamation Project (*H*) had geometric-mean selenium concentrations exceeding 12.5 μg/g and 33 percent in the Gunnison River Basin–Grand Valley Project (*F*) exceeded that level.

Study areas were classified as normal, elevated, and embyrotoxic based on the maximum geometric-mean selenium content of an eggset from the study area. Fourteen areas were classified as embryotoxic (table 21) because the geometric-mean selenium concentration exceeded the 6 μg/g threshold level in at least some of the egg sets. Six areas were classified as normal because all geometric-mean selenium concentrations were less than 3 μg/g. Four areas were classified as elevated because the maximum geometric-mean selenium concentration was greater than 3 μg/g but less than 6 μg/g

When irrigation-induced contamination is severe, effects on wildlife populations can be overtly evident. The confirmed presence of deformed embryos at Kesterson Reservoir and at 4 of the 26 study areas (*F, H, N,* and *Y*) provide dramatic evidence of selenium effects. Deformities of bird embryos are a clear, unambiguous indication that wildlife is being harmed by a contaminant. However, tens to hundreds of embryos must be examined to determine if deformities are occurring in an area, but in most study areas few or no embryos were examined. If the geologic and climatic conditions described in the sections “Sources of Selenium,” p. 49 and “Climate,” p. 54, characterize these areas, deformities may be occurring even though none were observed.

Embryos having multiple overt deformities like those from Kesterson Reservoir were not found in 22 of the 26 areas. The apparent lack of clearly evident effects on aquatic biota and wildlife does not necessarily mean that biological effects were not occurring in the 22 areas. The apparent lack of biological effects in the Gunnison River Basin–Grand Valley Project (*F*; Lemly and others, 1993; Butler and others, 1994) was interpreted by Canton and Van Derveer (1997, p. 1258) to mean that biological effects were not occurring even though selenium concentrations were elevated in the water. A deformed embryo having symptoms of selenium toxicosis later was found in the area, which indicates the danger in assuming that a lack of evidence means a lack of biological effects.



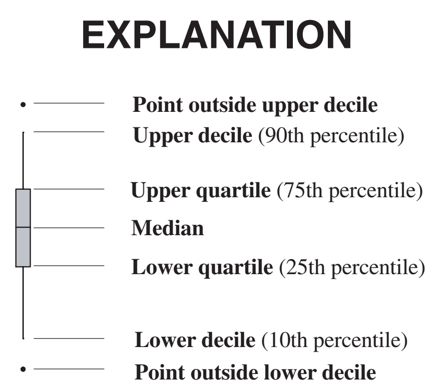


FIGURE 29. Geometric-mean concentrations of selenium in sets of avian eggs from National Irrigation Water Quality Program (NIWQP) study areas. Each set represents a distinct population of breeding birds.

TABLE 21. *Classification of National Irrigation Water Quality Program study areas by selenium content of avian eggs*

[Symbols: —, not applicable; <, less than; >, greater than]

Study area		Number of eggs analyzed for selenium content		Greatest selenium concentration[2] (micrograms per gram)	Area classification[3]	Area ranking[4]	Number of embryos assessed[7]	Selenium-related bird deformities[5]
Identifier[1]	Name	Individuals	Sets					
A	American Falls Reservoir, Idaho	13	7	2.0	Normal	22.5	0	No
B	Angostura Reclamation Unit, South Dakota	8	2	2.5	Normal	21	0	No
C	Belle Fourche Reclamation Project, South Dakota	10	5	9.5	Embryotoxic	12	0	No
D	Columbia River Basin, Washington	29	7	3.3	Elevated	16.5	<58	No
E	Dolores–Ute Mountain area, Colorado	15	10	18	Embryotoxic	5.5	<15	No
F	Gunnison River Basin–Grand Valley Project, Colorado	91	48	42	Embryotoxic	4	>65	Yes
G	Humboldt River area, Nevada	37	5	3.2	Elevated	18	<37	No
H	Kendrick Reclamation Project, Wyoming	400	18	121	Embryotoxic	1	137	Yes
I	Klamath Basin Refuge Complex, California–Oregon	31	5	1.9	Normal	24	0	No
J	Lower Colorado River valley, California–Arizona[6]	2	1	12	Embryotoxic	10	0	No
K	Lower Rio Grande valley, Texas	0	0	—	—	--	0	No
L	Malheur National Wildlife Refuge, Oregon	47	13	2.7	Normal	20	<47	No
M	Middle Arkansas River Basin, Colorado–Kansas	9	3	7.8	Embryotoxic	13	0	No
N	Middle Green River Basin, Utah	399	175	74	Embryotoxic	2	173	Yes
O	Middle Rio Grande, New Mexico	15	8	2.0	Normal	22.5	0	No
P	Milk River Basin, Montana	9	3	2.9	Normal	19	0	No
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	19	9	3.3	Elevated	16.5	0	No
R	Pine River area, Colorado	23	9	14	Embryotoxic	9	<23	No
S	Riverton Reclamation Project, Wyoming	15	7	17	Embryotoxic	7	0	No
T	Sacramento Refuge Complex, California	20	6	3.9	Elevated	15	18	No
U	Salton Sea area, California	128	9	6.2	Embryotoxic	14	65	Possible
V	San Juan River area, New Mexico	13	9	18	Embryotoxic	5.5	7	Possible
W	Stillwater Wildlife Management Area, Nevada	92	24	9.9	Embryotoxic	11	109	Possible
X	Sun River area, Montana	620	134	68	Embryotoxic	3	759	Possible
Y	Tulare Lake Bed area, California	12	1	16	Embryotoxic	8	93	Yes
Z	Vermejo Project area, New Mexico	0	0	—	—	--	0	No

[1] Used in figure 2 to show locations of study areas.

[2] Greatest geometric-mean selenium concentration of an egg set from the study area.

[3] According to greatest selenium concentration of the egg sets from study area: Elevated, 3 to 6 micrograms per gram; embryotoxic, greater than 6 micrograms per gram; normal, less than 3 micrograms per gram.

[4] Ranking of 24 study areas from most to least contaminated on the basis of the greatest observed selenium concentration in a set of bird eggs.

[5] Yes, birds and embryos observed having multiple overt deformities and selenium toxicosis confirmed by tissue analysis; possible, deformed birds and embryos observed but selenium toxicosis not identifed as cause; no, deformed birds and embryos not observed.

[6] Data for two Yuma clapper rail eggs were collected from the study area during the National Irrigation Water Quality Program investigation (William G. Kepner, U.S. Fish and Wildlife Service, written commun., 1989) but were not published in the report by Radke and others (1988). That data is presented here but was not used in the subsequent section "Avian-egg Risk Assessment," p. 86.

[7] For some study areas, reports describing investigations did not specify number of embryos assessed. This uncertainty is reflected herein by use of symbols "<," or ">" preceding number of assessed embryos. See text for discussion. Sample sizes in this table may also differ from those listed for 'Birds' in table 9 because that table includes samples of all types of bird tissue and excludes eggs that were examined but not chemically analyzed.

O'Toole and Raisbeck (1998, p. 383-384) commented that several authors had predicted that selenium-induced problems in waterfowl were likely in the Stillwater Wildlife Management Area (*W*) but that the detailed study by Hoffman (1994) did not report terata in the area. However, reduced hatchability caused by selenium may be occurring in one part of the study area. The highest selenium concentrations (median 8.9 µg/g, $n = 31$) in eggs sampled near the Stillwater Wildlife Management Area were from the Fernley Wildlife Management Area, which is about 35 mi west of the main study area. Hallock and others (1993) reported the results of an experiment in which 42 eggs from the Stillwater Wildlife Management Area and 12 eggs from the Fernley Wildlife Management Area were collected and incubated in the laboratory to assess hatchability. Of the 42 eggs from the low-selenium Stillwater Wildlife Management Area, 2 (4.8 percent) failed to hatch. The Blyth-Still-Casella 95-percent confidence interval for that outcome is 0.85-15.7 percent. Of the 12 eggs from the Fernley Wildlife Management Area, 2 (16.7 percent) failed to hatch. Thus, the 16.7 percent observed fail-to-hatch rate for Fernley eggs falls outside the upper confidence boundary for the Stillwater eggs. Although the two rates are not conclusively distinguishable by statistical hypothesis testing because of low statistical power associated with the small sample size from Fernley, the association of lower hatchability with the area having the highest selenium concentrations in eggs raises the possibility that selenium may have had an effect even though terata were not found. The small sample size makes it difficult to determine whether selenium affected hatchability; even if one-quarter of the eggs from the Fernley area had failed to hatch, the differences in the rates would not have been statistically significant.

Selenium-caused embryonic deformities are found only when two conditions are met: high-enough ambient selenium concentrations to cause deformities and intensive-enough sampling effort to find deformed embryos if present. For instance, calculations using the binomial theorem show that in an area where selenium is causing a Kesterson-like 5 percent of the embryos to be deformed, almost 60 eggs containing assessable embryos must be collected to attain a 95-percent probability that one or more of the eggs contains a deformed embryo. If only 10 assessable eggs are collected, the probability is 60 percent that none of the eggs will contain a deformed embryo. In 20 of the areas, fewer than 50 eggs were analyzed for selenium content (table 21). In only 8 of the 26 study areas is it certain that 10 or more eggs were assessed for embryo status (table 21). In several areas the number of embryos assessed for terata was not specified in reconnaissance- and detailed-study reports (table 1). Embryos can be assessed without being submitted for chemical analysis, or eggs submitted for chemical analysis may not contain assessable embryos. Uncertainty in the number of assessed embryos is reflected by use of "<" or ">" symbols in table 21. For instance, in the Columbia River Basin (*D*), 58 eggs were analyzed for trace elements and organochlorine compounds, but the number of embryos assessed is listed as <58 because some eggs did not contain assessable embryos. The number of eggs that could be analyzed and examined for terata during reconnaissance investigations was limited in part because of the need to balance the number of areas that could be investigated with the degree of detail of the investigations.

Statements that deformities were not observed cannot be considered evidence that deformities are not occurring unless information is given about the intensity of the sampling effort. Consider the two following statements:

(1) No deformed embryos were found.

(2) No deformed embryos were found in 300 eggs with assessable embryos. The deformity rate in the area is 1 percent or less because otherwise the probability is 95 percent that one or more deformed embryos would have been found.

Only the second statement can be considered evidence that deformities are not occurring in an area.

Thus, the low selenium concentrations in surface water in the Malheur National Wildlife Refuge (*L*; table 15) combined with the lack of observed deformities in 47 eggs probably means that deformities are not occurring at an elevated rate. But in the San Juan River area (V), selenium concentrations in surface water were elevated and no deformities were observed in the 7 egg samples. An appropriate conclusion for this area could be that deformities may have been occurring at rates of as much as 20 percent, but if only 7 eggs were examined, 21 percent of the time no deformity would be found.

Because some birds are more susceptible to selenium contamination in wetlands than others, further discussion of how to interpret this type of negative result (deformities were not found) is warranted. Knowledge of which species were collected is important in analyzing the results because statistically significant results may be biologically meaningless if the only birds collected are not susceptible to selenium poisoning. For example, in the Belle Fourche Reclamation Project (*C*), eggs of several species of birds, including red-winged blackbirds, were collected. The four blackbird eggs collected had selenium concentrations in the normal range, which might be expected even in a contaminated area. Red-winged blackbird diet is principally seeds, spiders, and insects (Welty, 1975), which, being terrestrial, would contain low concentrations of selenium even in areas where wetlands contain elevated concentrations of selenium. However, the three grebe eggs collected in the Belle Fourche Reclamation Project contained embryotoxic amounts of selenium, which might be expected because grebes eat fish that live in the contaminated water. Although the selenium concentrations in the grebe eggs were much less than values associated with teratogenesis, even if 20 percent of the grebe embryos in the area were deformed, the probability is greater than 50 percent that collecting only three grebe eggs would not reveal a deformity.

Most of the 26 NIWQP studies do not provide definitive data on whether deformities are occurring because only studies that detected deformities, or sampled large numbers of embryos (~≥100) without finding deformities, provide adequate data. In only five study areas (*H*, *N*, *W*, *X*, *Y*) were more than 100 embryos examined. A deformed embryo was detected in one additional study area (*F*). Thus, of the 24 study areas from which bird eggs were collected, definitive data for assessing teratogenic effects were collected from only six. For those six areas, selenium-induced teratogenic effects were confirmed in four areas (*F, H, N, and Y*). In all four areas, teratogenic effects would have been expected *a priori* because selenium concentrations in at least some of the collected eggs exceeded concentrations associated with embryo deformities in laboratory experiments on mallard ducks (Heinz and others, 1989).

Because all twenty-four NIWQP studies that included collection of avian eggs were specifically designed to asses selenium concentrations in these eggs, ultimately, NIWQP must rely on egg selenium concentrations as a surrogate measure of selenium-induced adverse effects for most of the study areas. Furthermore, because egg viability (hatchability) is a much more sensitive endpoint than embryo teratogenesis for selenium-induced effects (Skorupa, 1999), the most prudent approach is to compare egg selenium concentrations to pre-existing guidelines for assessing risk of selenium-induced egg inviability, also known as embryotoxicity (i.e. the death of an embryo regardless of whether the embryo was deformed or normal at the time of death).

TAXONOMIC AND FEEDING GUILD ANALYSIS OF AVIAN-EGG DATA

Eggs were sampled from 34 species of birds belonging to 10 orders (table 22). Geographically, the most extensively sampled orders were the Anseriformes (represented in NIWQP samples by geese and ducks), Gruiformes (represented in NIWQP samples by coots), and Charadriiformes (represented in NIWQP samples by avocets, killdeer, and stilts). Samples from those three orders were collected from 21 (81 percent) of the 26 NIWQP study areas. On the basis of numbers of sets of eggs collected, American coots (n = 65), mallards (n = 61), and American avocets (n = 44) were the three species most frequently sampled and also were the only species whose eggs were collected from 10 or more different NIWQP study areas. Every NIWQP study area that was sampled for avian eggs was represented by at least one of four groups of birds: ducks, recurvirostrids (avocets and stilts), coots, and blackbirds. From a regional risk-assessment perspective, those are the four groups of birds for which it would be most useful to have rigorous embryonic exposure-response curves. Fortunately, statistically rigorous exposure-response curves based on field data are available for two of those taxonomic groups, ducks (U.S. Department of the Interior, 1998) and recurvirostrids (Skorupa, 1998).

Of the 34 species of birds sampled during NIWQP investigations, sets of eggs having a geometric-mean selenium content of at least 12.5 µg/g, a high-risk threshold (CH2M HILL, 2002), were documented for 16 species (table 22). All three species of grebes yielded at least one high-risk set of eggs, as did four of five species of shorebirds. Among waterfowl (Anseriformes), five of eleven species yielded at least one high-risk set of eggs. By comparison, 24 of the 34 species sampled for the NIWQP yielded one or more sets of eggs having a geometric-mean selenium content of at least 6 µg/g, the threshold for embryotoxicity associated with intermediate avian sensitivity to selenium (Skorupa, 1998). Among 10 species of ducks, only American wigeon did not yield at least one set of potentially selenium-effected eggs; however, only one wigeon egg was sampled.

Egg-set data were examined to determine if some feeding guilds are more at risk to selenium poisoning than others. Waterbird taxa for which eggs were collected (table 22) were classified into one of three feeding guilds (herbivore, insectivore, and piscivore) using dietary information from Martin and others (1951), Storer and Nuechterlein (1992), Parsons and Master (2000), Robinson and others (1999), and Jackson and Jackson (2000). For the following analysis, nine taxa whose diet is almost exclusively restricted to one of the three guilds were used. American Coot and Canada Goose were classified as herbivores; American Avocet, Common Snipe, Killdeer, and Black-necked Stilt were classified as insectivores; and Western Grebe, Snowy Egret, and Black-necked Night Heron were classified as piscivores. Eggs forming 157 sets from these taxa were collected from study areas where the 75th percentile selenium concentration in surface water exceeded 5 µg/L (table 15). The median geometric-mean selenium concentration in the egg sets increases with trophic level of the dietary items (fig. 30A). Geometric-mean selenium concentration in nearly 50 percent of egg sets from insectivorous birds and more than 75 percent of egg sets from fish-eating birds exceed 6 µg/g. Selenium concentrations for 39 percent of the egg sets from herbivorous birds fall in the normal range (less than 3 µg/g) while only 7 and 0 percent, respectively, of egg sets from insect- and fish-eating birds fall in the normal range.

These results suggest that herbivorous birds may bioaccumulate less selenium than insect- and fish-eating birds, however, these results may just be an artifact of sampling. Water samples were not collected at nesting sites for nearly 2/3 of the 157 egg sets and, hence, the apparent lower risk for herbivorous birds could result from a larger percentage of their eggs being collected at sites where water is uncontaminated. To test this alternative explanation, data were plotted for 32 egg sets where selenium concentrations in water were measured and were greater than 5 µg/L (fig. 30B). These data also indicate herbivorous birds bioaccumulate less selenium than insect-eating birds. Selenium concentrations for 14 percent of the egg sets

TABLE 22. *Taxonomic distribution of National Irrigation Water Quality Program avian-egg samples analyzed for selenium*

[Taxonomic nomenclature according to American Ornithologists' Union (1998). Tabulated data exclude 13 samples that were not identified to species level. Abbreviation: µg/g, micrograms per gram]

Species	Number of study areas	Number of samples[1]	Number of sets[2]	Maximum geometric-mean selenium[3] (µg/g, dry weight)
Anseriformes (Screamers, Swans, Geese, and Ducks)				
Anas acuta (northern pintail)	4	49	15	8.5
Anas americana (american wigeon)	1	1	1	1.4
Anas clypeata (northern shoveler)	3	59	22	12
Anas cyanoptera (cinnamon teal)	6	60	21	37
Anas discors (blue-winged teal)	2	7	5	9.0
Anas platyrhynchos (mallard)	16	170	61	52
Anas strepera (gadwall)	5	143	39	21
Aythya affinis (lesser scaup)	1	49	19	9.3
Aythya americana (redhead)	4	46	13	20
Branta canadensis (canada goose)	3	175	24	19
Oxyura jamaicensis (ruddy duck)	3	20	6	9.6
Charadriiformes (Shorebirds, Gulls, Auks, and Allies)				
Charadrius vociferus (killdeer)	3	13	9	21
Gallinago gallinago (common snipe)	3	7	6	21
Himantopus mexicanus (black-necked stilt)	4	142	15	33
Larus californicus (california gull)	1	2	1	2.8
Phalaropus tricolor (Wilson's phalarope)	1	6	2	12
Recurvirostra americana (american avocet)	10	300	44	86
Ciconiiformes (Herons, Ibises, Storks, and Allies)				
Ardea herodias (great blue heron)	1	6	2	2.7
Botaurus lentiginosus (american bittern)	1	1	1	5.3
Egretta thula (snowy egret)	1	3	2	6.9
Nycticorax nycticorax (black-crowned night-heron)	4	32	9	18
Falconiformes (Diurnal Birds of Prey):				
Circus cyaneus (northern harrier)	2	3	3	5.2
Galliformes (Gallinaceous Birds):				
Colinus virginianus (northern bobwhite)	1	1	1	4.1
Phasianus colchicus (ring-necked pheasant)	1	1	1	7.0
Gruiformes (Cranes, Rails, And Allies):				
Fulica americana (american coot)	15	344	65	49
Passeriformes (Passerine Birds)				
Agelaius phoeniceus (red-winged blackbird)	7	45	20	18
Euphagus cyanocephalus (Brewer's blackbird)	1	2	1	4.5
Xanthocephalus xanthocephalus (yellow-headed blackbird)	4	43	26	21
Pelecaniformes (Totipalmate Swimmers)				
Pelecanus erythrorhynchos (american white pelican)	1	5	1	2.8
Phalacrocorax auritus (double-crested cormorant)	2	11	3	2.4
Podicipediformes (Grebes)				
Aechmophorus occidentalis (western grebe)	4	21	5	25
Podiceps nigricollis (eared grebe)	3	242	12	121
Podilymbus podiceps (pied-billed grebe)	5	28	17	74
Strigriformes (Owls)				
Asio flammeus (short-eared owl)	1	1	1	3.4

[1]Sample may consist of individual egg or individual composite of several eggs, depending on size of particular species' eggs.

[2]Set is distinct species-by-site-by-year permutation that conceptually represents eggs sampled for distinct breeding population of birds; may be either single egg or composite.

[3]Measured in any egg set for each species; geometric means greater than 20 µg/g indicate high potential for reproductive impairment.

from herbivorous birds fall in the normal range and the median selenium concentration for herbivorous birds is substantially lower than for insectivorous birds. Even if herbivorous birds bioaccumulate less selenium than insectivorous and piscivorous birds, however, it does not indicate they are at less risk. It is both the degree of bioaccumulation and the species sensitivity to selenium exposure that determines the magnitude of toxic effects.

Although herbivorous birds may bioaccumulate less selenium, a minimum of 86 percent of the eggs from all feeding guilds exceeded normal background values. Thus, at a gross level of examination, it does not appear that any waterbird feeding guilds are particularly well buffered from exposure to selenium contamination. This agrees with results of food-chain

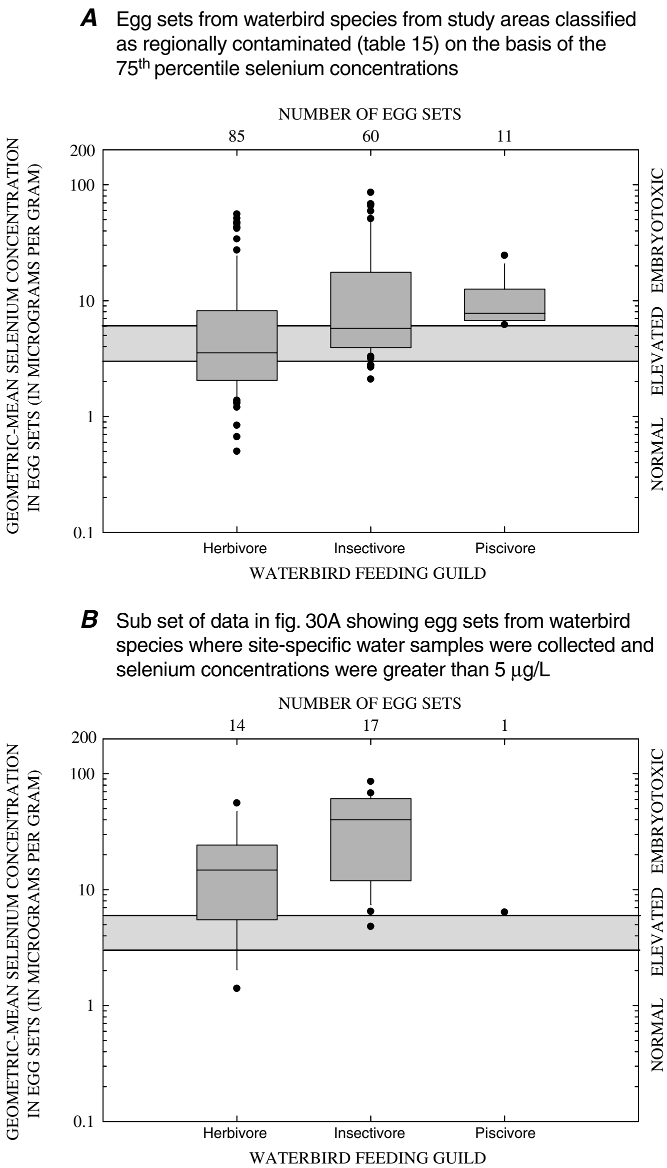


FIGURE 30. Geometric mean concentrations of selenium in sets of waterbird eggs from three feeding guilds.

studies at selenium-contaminated wetlands, which have consistently found food-chain uptake of selenium to be pervasive throughout aquatic food webs (Saiki and Lowe, 1987; Hothem and Ohlendorf, 1989; Schuler and others, 1990). Because nearly all the NIWQP eggs come from aquatic species of birds, analyzing the data set in aggregate should introduce minimal bias due to taxonomic variation in the samples from each NIWQP study area. This would not be true if certain waterbird feeding guilds appeared to be strongly buffered from selenium exposure or if some study areas included many samples of terrestrial birds. In summary, mixed-species collections of waterbird eggs from the NIWQP study areas normally should accurately reflect local contaminant conditions. Increasing levels of selenium contamination should normally lead to comparable increases in mean selenium content of mixed-species egg collections.

PREDICTION OF SELENIUM CONTAMINATION OF WATER

An important goal of the data synthesis was the creation of tools to help managers identify areas for which they are responsible that may be at risk from irrigation-induced selenium contamination. The tools range in scope from identifying broad geographic areas where selenium contamination is likely to assessing the probability that selenium concentrations in a specific lake exceed the USEPA chronic criterion for selenium. The predictive tools presented in this section were described in detail by Naftz (1996a), Nolan and Clark (1997), Seiler (1995), and Seiler and others (1999). A summary of the predictive tools and a discussion of when it is appropriate to use each of the tools follows.

PREDICTION USING GEOLOGIC, CLIMATIC, AND HYDROLOGIC DATA

The severity of selenium contamination is related to geology, climate, and hydrology (see sections titled “Sources of Selenium,” p. 49; “Climate,” p. 54; and “Hydrology,” p. 54). These types of data are readily available and can be used to predict the likelihood of selenium contamination. Two types of management tools have been prepared. The first is a map based on geologic and climatic data that may be used to identify broad geographic areas where selenium contamination is likely; Seiler and Skorupa (1995) and Seiler and others (1999) discussed the derivation and use of this tool. The second management tool is a decision tree in which answers to questions about the geology, hydrology and climate are used to predict the likelihood that a specific irrigation project is contaminated. Seiler (1995) discussed the derivation and use of this tool.

The EI is used extensively in applying these two tools. The critical EI values selected are empirical and were based on an examination of data for those study areas where there is a known geologic source of selenium (fig. 27*B*). Although additional information may require revision of the numbers in the future, an EI value of 2.5 was considered important because it was intermediate between the value for an uncontaminated area (*P*, *EI* = 1.9, fig. 27*B*) and those for the areas with the lowest EI's where selenium contamination occurred (*B* and *C*; *EI* = 2.8, fig. 27*B*). An EI value of 3.5 was considered important because in all but 1 of the 12 study areas, if the EI exceeded 3.5, more than 25 percent of the selenium concentrations exceed the chronic criterion for selenium.

BROAD GEOGRAPHIC AREAS

Broad geographic areas of the Western United States susceptible to irrigation-induced selenium contamination can be identified by creating a map based on geology and climate. Areas in the Western United States susceptible to irrigation-induced selenium contamination are identified in figure 31. The map was created by using a GIS to overlay geology data—areas where Upper Cretaceous or Tertiary marine sedimentary rocks form the bedrock (fig. 20) and climate data—areas where the EI is greater than 2.5 (fig. 22). Seiler and others (1999) presented specific details about how the map was created. The GIS geology data layer was created by manipulating data from the geologic map of the United States, compiled by King and Beikman (1974) and later digitized by Schruben and others (1994). The GIS climate data layer, showing areas where the EI exceeded 2.5, was created by manipulating evaporation and precipitation data in the GIS.

About 160,000 mi^2 of land was identified as susceptible to selenium contamination if irrigated (fig. 31; table 23). Examination of satellite imagery indicated that about 4,100 mi^2 of land that is actively irrigated for agriculture in the Western United States was found to be within areas mapped as susceptible to irrigation-induced selenium contamination (Seiler and others, 1999). The greater the EI, the more likely are selenium problems in areas having sources of selenium. Approximately 52,600 mi^2 of land was identified as being the most susceptible to selenium contamination because of EI values greater than 3.5.

Table 23. *Amount of land in Western United States where bedrock consists of Upper Cretaceous or Tertiary marine sedimentary rocks and where evaporation index exceeds four threshold values*

Threshold value for evaporation index	Area in Western United States (square miles)	Percentage of total area of Western United States
Greater than 2.5	160,000	8.7
Greater than 3.0	83,300	4.5
Greater than 3.5	52,600	2.9
Greater than 5.0	17,300	0.9

Irrigated land that is adjacent to areas mapped as susceptible to selenium contamination should be considered potentially susceptible because selenium can be transported from source areas in mountains to irrigated areas in adjacent valleys through processes of active weathering, alluvial-fan building, and local drainage. In California, all areas mapped as susceptible are in mountain ranges where no agricultural irrigation was done. Another reason to consider land as provisionally susceptible if it is adjacent to land mapped as susceptible is that the bedrock in the area may be seleniferous if derived by reworking seleniferous marine sedimentary deposits. The NIWQP data clearly indicate that selenium contamination can develop in areas of Tertiary continental sedimentary bedrock if Upper Cretaceous marine sedimentary rocks are nearby.

The susceptibility map correctly classified 22 of the 26 NIWQP study areas (fig. 32). Ten of 12 areas classified as uncontaminated were correctly identified. The first uncontaminated area incorrectly identified was the Sacramento Refuge Complex in California (*T*) which is adjacent to an area mapped as susceptible. It has one of the lowest EI values (2.6) of the NIWQP areas; however, being near seleniferous rocks may not result in contamination if the EI is low. In the second area, the Milk River Basin in Montana (*P*), all surface water samples were collected during a flood year. Data from Lambing and others (1988) and Presser and others (1994) indicate this area is contaminated during more normal circumstances.

The two areas classified as seleniferous and 10 of the 12 areas classified as contaminated (table 15) were identified correctly because they are on or adjacent to areas mapped as susceptible (figs. 31 and 32). The two contaminated areas that were incorrectly identified are the Salton Sea (*U*) and Sun River (*X*) area. The Salton Sea area could not be identified by the criteria used to construct the map because selenium is brought into the area in water used for irrigation. The Sun River area was not identified correctly because the climate map used to construct figures 31 and 32 are inaccurate in central Montana (Seiler and others, 1999).

The validity of the map (fig. 31) was assessed by plotting several independent test areas where selenium investigations have been done and determining whether the map correctly identified the selenium-contaminated areas. Kesterson National Wildlife Refuge (in San Joaquin Valley in California), an area of known selenium contamination resulting from irrigation drainage (Ohlendorf, Hoffman, and others, 1986), was correctly identified as susceptible because it is adjacent to an area mapped as susceptible (fig. 32).

Selenium contamination was discovered in 1996 at Red Rock Ranch (fig. 32), an experimental agroforestry farm south of Kesterson Reservoir. Irrigation drainwater at the Red Rock

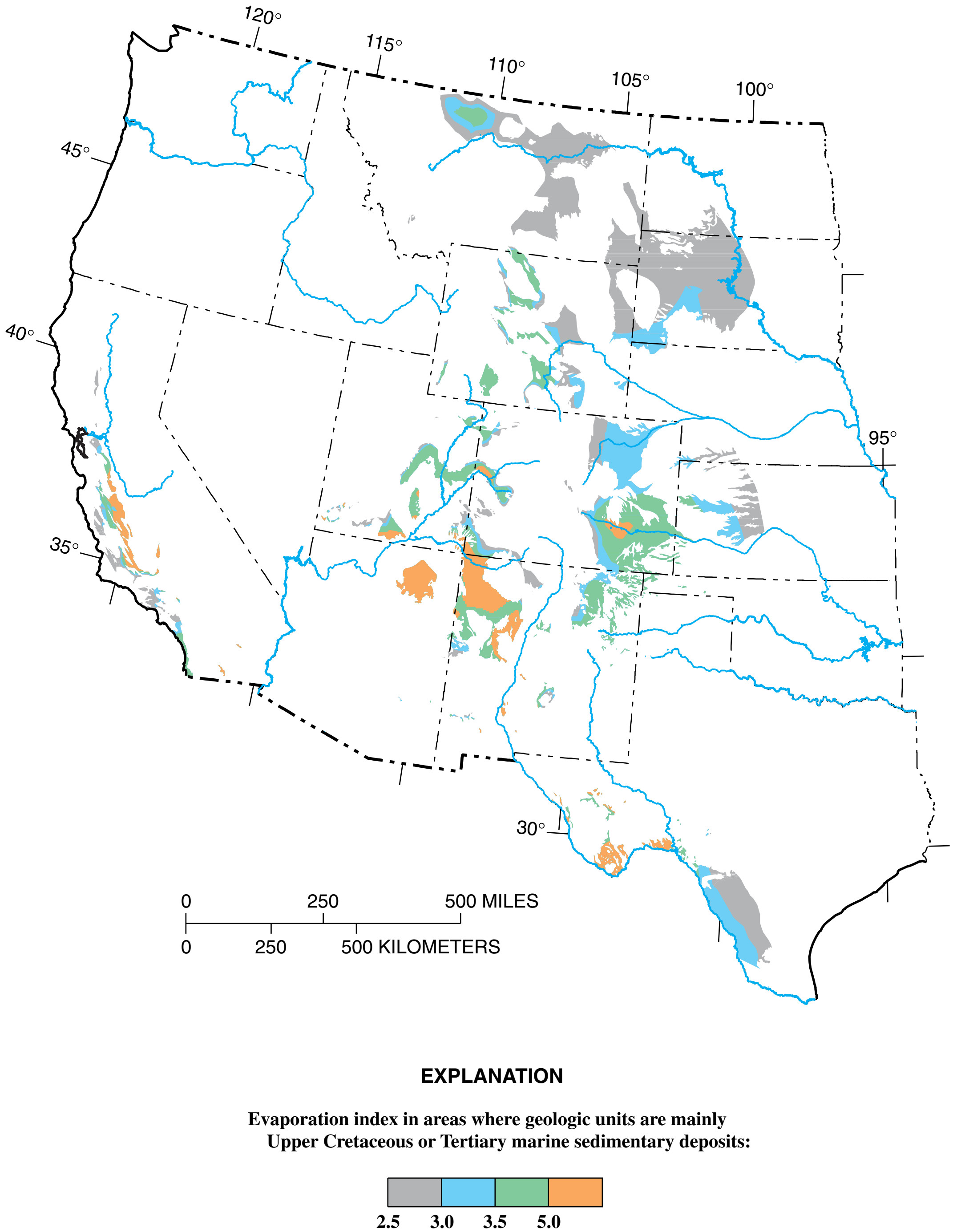
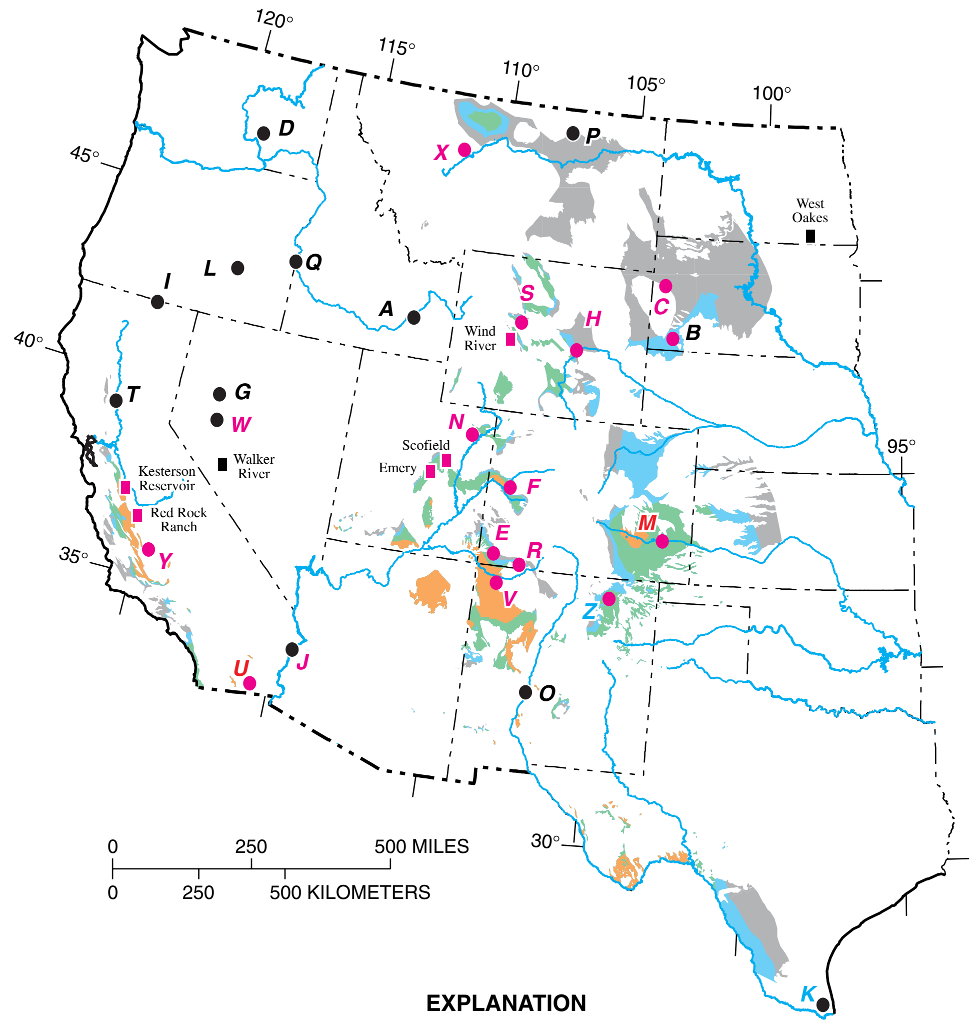


FIGURE 31. Areas in Western United States that are identified as susceptible to irrigation-induced selenium contamination on basis of Upper Cretaceous or Tertiary marine sedimentary bedrock (fig. 20) and evaporation index greater than 2.5 (fig. 22). For base credit, see figure 1.



EXPLANATION

Evaporation index in areas where geologic units are mainly Upper Cretaceous or Tertiary marine sedimentary deposits:

2.5 3.0 3.5 5.0

National Irrigation Water Quality Program study areas:

W ● Area classified as uncontaminated and where some bird eggs contain embryotoxic concentrations of selenium

Y ● Area classified as seleniferous or contaminated and where some bird eggs contain embryotoxic concentrations of selenium

T ● Area classified as uncontaminated and where bird eggs do not contain embryotoxic concentrations of selenium

B ● Area classified as seleniferous or contaminated but where bird eggs do not contain embryotoxic concentrations of selenium

K ● Area classified as uncontaminated and where bird eggs were not collected

Z ● Area classified as contaminated and where bird eggs were not collected

Test areas and other areas or sites discussed in text:

West Oakes ■ Area or site where surface water is not selenium contaminated

Scofield ■ Area or site where surface water is selenium contaminated

FIGURE 32. National Irrigation Water Quality Program study areas, test areas, and areas in Western United States susceptible to irrigation-induced selenium contamination. For locations and descriptions of study areas (*A*–*Z*), see figure 2 and table 1.

Ranch was reused for irrigation of salt-tolerant plants and ultimately contained extremely high concentrations of selenium—1,600 µg/L in the water used for the last crop and more than 11,000 µg/L in shallow evaporation ponds (Skorupa, 1998). Black-necked stilts nesting in the area were exposed to the water and almost 60 percent of the eggs in the population contained deformed embryos (Skorupa, 1998). The Red Rock Ranch is adjacent to an area mapped as susceptible. Data from Kesterson Reservoir and Red Rock Ranch indicate the importance of provisionally treating areas as susceptible if they are adjacent to areas mapped as susceptible.

In the mid-1980's, the West Oakes Irrigation Area of North Dakota (fig. 32) was investigated for potential selenium contamination because of its association with sediments of Cretaceous age. The West Oakes Irrigation Area was identified correctly as being in an area not susceptible to irrigation-induced selenium problems; selenium concentrations in surface water were less than 2 µg/L, and the greatest selenium concentration in ground water was 4 µg/L (Goolsby and others, 1989).

The validity of the map also was assessed by using NIWQP data other than the data analyzed to make the susceptibility maps. In 1992–93, the NIWQP collected water samples from the Wind River Indian Reservation in Wyoming (fig. 32). This area is on and adjacent to land mapped as susceptible to selenium contamination, a classification that is supported by data from Grasso and others (1995). Of 28 water samples collected from the Little Wind Irrigation Unit in 1993, 6 had selenium concentrations that equaled or exceeded 5 µg/L, the maximum being 17 µg/L. Of 25 water samples collected during a subsequent investigation of the Little Wind River Irrigation Unit in 1995 (Clark and Sadler, 1996), 6 had selenium concentrations that exceed 5 µg/L, the maximum being 49 µg/L.

Because biological data were not analyzed to create the susceptibility map, those data can provide an independent test of the map. Areas were classified as embryotoxic, elevated, or normal on the basis of the selenium content of bird eggs from the areas (table 21). In 14 of the 24 study areas where bird eggs were collected, the geometric-mean selenium concentration in at least one set of avian eggs was classified as embryotoxic (table 21). The map identified 10 of those 14 areas as susceptible to irrigation-induced selenium contamination (fig. 32). The four areas classified as embryotoxic in table 21 that were not identified from the map are the Lower Colorado River valley (*J*) in California and Arizona, the Stillwater Wildlife Management Area in Nevada (*W*), the Salton Sea area (*U*), and the Sun River Area in Montana (*X*). Even though they are not identified on the susceptibility map, elevated selenium concentrations in water are known to occur in the Stillwater Wildlife Management Area (*W*), the Salton Sea area (*U*), and Sun River areas (*X*) and likely occur in backwater areas in the Lower Colorado River valley (*J*; Seiler and others, 1999). The Lower Colorado River valley (*J*) and the Salton Sea area (*U*) were not identified as susceptible because selenium is brought into the areas in Colorado River water. In the Stillwater Wildlife Management Area (*W*), selenium is not a general problem; all of the embryotoxic eggs are from two isolated ponds whose source of selenium is not known (Seiler and others, 1999). The Sun River area (*X*) was not identified because the climate map used to construct figures 31 and 32 is inaccurate in central Montana (Seiler and others, 1999).

Two areas that were not classified as embryotoxic are on areas mapped as susceptible (fig. 32). The Milk River Basin (*P*) is classified as normal although it probably is contaminated most years (see section titled "Temporal Changes in Selenium Concentration," p. 58). The Angostura Reclamation Unit (*B*) is classified as normal, but only eggs from an unidentified species of blackbird were collected. Species of blackbirds that nest in the area primarily consume terrestrial seeds and insects and thus may not show evidence of selenium problems. The diet of the rusty blackbird, which may winter in the area, is mostly aquatic beetles and their larvae (Martin and others, 1951); however, it does not nest in the area.

INDIVIDUAL LOCATIONS

The susceptibility map has the advantages that it is graphical, is easy to use, and is amenable to use with land-use overlays. However, not all areas susceptible to irrigation-induced selenium contamination are identified because important hydrologic information about terminal ponds and information about upstream sources of selenium are not readily mappable.

Seiler (1995) presented a decision tree (fig. 33) that uses answers to questions about the geology, climate, and hydrology of a location to provide an estimate of the likelihood that selenium contamination will occur there. The decision tree ranks a target irrigation area into one of four classes on the basis of the likelihood of significant problems resulting from selenium contamination: selenium problem is unlikely; selenium problem is possible; selenium problem is likely; or selenium problem is very probable. From these four classes, a manager can assess the need to collect additional information.

To rank the likelihood that an area is contaminated, four basic questions about the geology, climate, and hydrology of the area must be answered:

(1) Are irrigated lands on or near an area where Upper Cretaceous or Tertiary marine sedimentary deposits form the near-surface bedrock?

(2) What is the EI of the area?

(3) Are terminal ponds or lakes in the area?

(4) Is a source of selenium upstream?

Answers to the first question can be obtained by plotting the location of the target area on a geologic map of the area. Calculating the EI for the second question requires obtaining the annual FWSE rate from the evaporation map by Farnsworth and others (1982) and the average annual

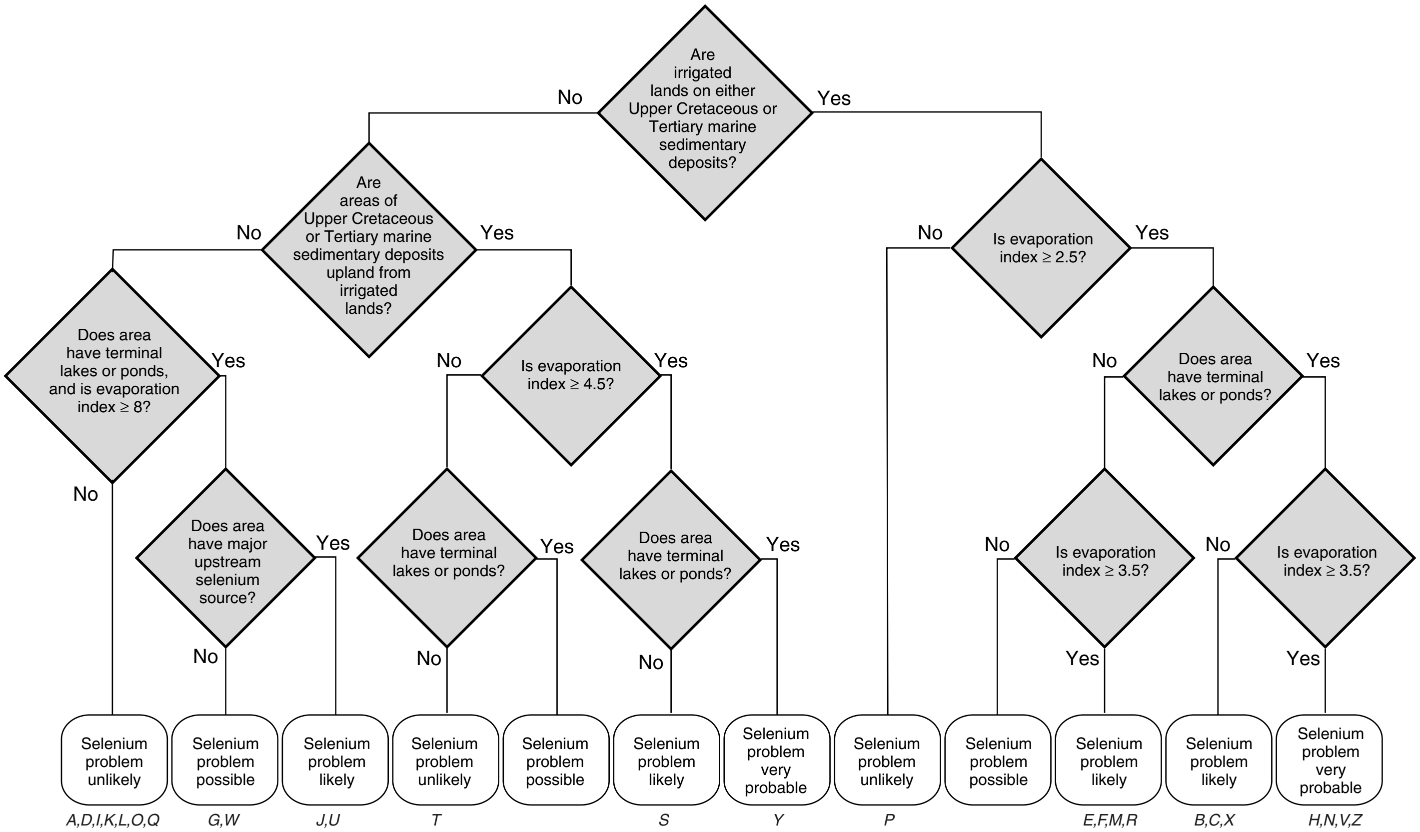


FIGURE 33. Prediction of likelihood of selenium contamination and classification of test areas and 26 National Irrigation Water Quality Program study areas used to derive decision tree. Letter identifies study area (fig. 2). Modified from Seiler (1995) and published with permission of American Society of Agronomy.

precipitation from records of individual weather stations or from State-scale precipitation maps such as those by Moody and others (1986). Answers to the last two questions can be obtained by examining topographic and geologic maps of the area and the watershed supplying it.

According to the study-area classifications determined using the decision tree (fig. 33), selenium contamination is unlikely in 9 of the 26 areas, and table 15 shows these 9 areas as uncontaminated. In 17 of the 26 areas, the likelihood of selenium contamination ranged from possible to very probable. In 12 of those 17 areas, selenium concentrations in more than 25 percent of the surface-water samples exceeded 5 µg/L, the USEPA chronic criterion for the protection of aquatic life. In five areas (*H, N, V, Y,* and *Z*) a selenium problem was ranked as very probable; those areas were ranked as the first, second, third, ninth, and fourteenth most contaminated areas on the basis of their 75th percentile selenium concentration (table 15).

Biological data collected as part of the NIWQP were used to assess the reliability of the decision tree. Selenium contamination was classified as being very probable in 5 of the 26 areas, and waterfowl deformities resembling those at Kesterson Reservoir were found in 3 of those 5 areas. Bird eggs were collected in eight of the nine areas where selenium contamination was classified as unlikely in figure 33; selenium concentrations in these eggs were within the normal range in five of the eight areas and were only slightly elevated in the other three (table 21). Bird eggs were collected in 16 of the 17 areas where the likelihood of selenium contamination ranged from possible to very probable; selenium concentrations in the eggs from 14 of these 16 areas were in the embryotoxic range.

Samples of two yuma clapper rail eggs collected near Havasu National Wildlife Refuge in Arizona contained an average of 12.5 µg/g selenium (William G. Kepner, U.S. Fish and Wildlife Service, written commun., 1989), a concentration used in this report as a guideline for high-risk selenium-exposure (table 19). This supports the classification of the Lower Colorado River valley (*J*) as susceptible even though none of the water samples from the area exceeded the chronic criterion for selenium. The area was classified as uncontaminated (table 15); however, most of the samples on which that classification was based were from the main stem of the Colorado River. Birds frequenting biologically-productive areas in oxbows along the river that rarely receive inflow likely are exposed to water with higher selenium concentrations than those in the Colorado River itself. Water samples were not collected from these backwater areas as part of the NIWQP investigation.

Data from Kesterson Reservoir, California and the West Oakes Irrigation area, North Dakota, two areas not included in NIWQP studies, were used to assess the reliability of the decision tree. The likelihood of selenium contamination at Kesterson was ranked as very probable by the decision tree and as unlikely at West Oakes. Both these classifications are supported by reports describing the areas (Goolsby and others, 1989; Presser, 1994b). Although the Vermejo Project area (*Z*) was investigated as part of NIWQP, the data were not available during construction of the decision tree. The likelihood of selenium contamination at the Vermejo Project area was ranked as very probable, a ranking that is supported by the classification of the area as contaminated (table 15); also, Lusk and others (1991) stated that selenium concentrations in birds were at levels that may have been causing reproductive impairment.

LIMITATIONS OF THESE PREDICTIVE TOOLS

Many factors and processes that influence the actual amount or extent of selenium contamination in a given area are not considered in these management tools. For instance, hydrologic information such as the presence of terminal water bodies was not used in preparing the maps, and the amount of irrigated land in an area that is on Upper Cretaceous or Tertiary marine sedimentary rocks is not considered in the decision tree. Also not considered are the selenium content of the soils and chemically or microbiologically mediated redox reactions, all of which can affect how much selenium is transported from irrigated lands to wetlands or to other receiving water. These types of factors and processes purposely were not incorporated into the decision tree because such site-specific information commonly is not available to a resources manager performing an initial screening of areas to decide which warrant further investigation.

A fundamental assumption of the tools is that irrigated soils are derived from the underlying bedrock as generalized on the geologic map by King and Beikman (1974). Both the susceptibility maps and decision tree are constructed as if Upper Cretaceous and Tertiary marine sedimentary rocks were the only geologic source of selenium. Although these sediments are probably the most regionally important geologic source of selenium, users of the tools should be aware that marine sedimentary rocks of other ages, for example, the Phosphoria Formation of Permian age, may be important locally. Sediments that were deposited in similar environments or were formed by reworking Cretaceous deposits also may be seleniferous.

In the Western United States, glacial deposits of Pleistocene age conceal extensive areas of bedrock in Montana, North and South Dakota, and Nebraska. Selenium may not be a problem if the glacial deposits are thick and are not derived from Cretaceous rocks. Selenium may be a problem, however, in areas where the glacial deposits are derived from Cretaceous marine sedimentary rocks even though the underlying bedrock is not seleniferous.

The reliability of the susceptibility map depends on how accurately the maps used in the analysis portray the distribution of the critical geologic and climatic factors. Errors in the map of the EI result from interpolating values between contour intervals on the precipitation and evaporation maps. Errors from interpolation are greatest when the contouring intervals are large and are widely spaced on the map. Most of the error in the EI map results from interpolation errors in the precipitation map, where the contour intervals are typically 10 in. On the FWSE map, the contour interval is 5 in. except where the evaporation rate is greater than 80 in/yr. Inaccuracies in the EI map reduce the reliability of the map of susceptible areas in east-central Montana. Some areas in Montana that probably are susceptible to irrigation-induced selenium contamination are not identified on the map. For example, the Sun River area (*X*) is not mapped as susceptible (fig. 32) even though its EI exceeds 2.5 and irrigated lands are on Upper Cretaceous marine sedimentary rocks (table 18).

The map identifies areas on the basis of average climatic conditions. Under drought conditions, areas not identified on the map may be susceptible to irrigation-induced selenium contamination. Similarly, problems may not occur under flood conditions in areas mapped as susceptible. This is demonstrated by the Milk River Basin (*P*), which was mapped as susceptible (fig. 32); under normal circumstances this area probably is contaminated (see section titled “Temporal Changes in Selenium Concentrations”). However, for the NIWQP investigation, all data were collected during a wet year and selenium was not detected in any of the surface-water samples.

The map misses areas where selenium is brought into the area in water used for irrigation. This is demonstrated by the Lower Colorado River valley (*J*) and the Salton Sea area (*U*), which were not mapped as susceptible. Eggs from the Lower Colorado River valley were ranked as embryotoxic (table 21), and the Salton Sea area was classified as contaminated (table 15). These areas were not identified by the map because selenium is imported into the areas in Colorado River water.

PREDICTION USING LOGISTIC-REGRESSION MODEL

Logistic regression was used to predict the probability of exceeding the chronic criterion for selenium in surface water at a specific site. Nolan and Clark (1997) discussed the development and application of this predictive model.

Logistic regression differs from classical multivariate statistical methods in that the modeled response is the probability of being in a category, rather than the observed quantity of a response variable (Helsel and Hirsch, 1992). Logistic-regression models were validated by using a simulated data set of “unknowns.” Composite NIWQP data were partitioned into two halves and a logistic-regression model developed by using half the data set. The resulting model parameters were used with the other (simulated unknown) half of the data set to calculate theoretical probabilities of exceeding the chronic criterion for selenium in surface water. Results of this calculation were compared to observed probabilities.

The types of sites used in the logistic regression were streams, lakes, and surface drains; reference sites and ground-water sites were excluded. River sites on large (main-stem) streams originating outside an investigation area were included in two of the six models tested. The other four models included only small streams, lakes, and surface drains where local irrigation practices and geologic sources were assumed to be the primary influence on water quality. Data from the Vermejo Project area (*Z*) reconnaissance investigation and the Sun River area (*X*) detailed investigation were excluded because they had not been compiled regionally when the regression models were being developed and therefore lacked ancillary information necessary for the analysis.

The median selenium and total dissolved-solids (TDS) concentrations from each sampling site were calculated. Censored values for selenium were converted to one-half the detection limit (0.5 μg/L) before determining sampling-site median concentrations. Use of the median concentration at a sampling site reduced the influence of sites that were sampled intensively. Additionally, the median concentrations for selenium and TDS were log transformed to improve model performance.

Spearman correlation coefficients were computed to screen selenium concentrations, geologic source, TDS, and EI for possible use in logistic-regression models. TDS and EI were included in the correlation analysis as indicators of evaporative effects in semiarid to arid climates typical of the Western United States. The Spearman correlation coefficient for selenium and TDS from the local surface-water sites ($r = 0.45$; table 24) indicated that selenium concentrations in water samples from streams, lakes, and surface drains positively correlated with salinity. Similarly, Fujii and others (1988) and Tanji and Valoppi (1989) showed a positive relation between selenium and salinity in shallow ground water of the San Joaquin Valley in California.

The presence or absence of Upper Cretaceous marine sedimentary deposits had a significant effect on surface-water selenium concentration (fig. 21). A binary geologic variable (BGV) was created indicating the presence ($BGV = 1$) or absence ($BGV = 0$) of Upper Cretaceous marine sedimentary deposits composing bedrock in irrigated areas. The Spearman correlation coefficient for surface-water selenium concentration and the BGV was moderately high ($r = 0.64$; table 24). Source geology was represented in the regression by the BGV.

Spearman correlation coefficients (table 24) were greatest for BGV ($r = 0.64$) and TDS ($r = 0.45$). The positive correlations indicate increasing surface-water selenium concentration in the presence of Cretaceous sedimentary rocks and with increasing

TABLE 24. *Matrix of Spearman correlation coefficients (r) for variables considered in logistic-regression models*

[Based on data from local surface-water sites (excluding mainstem and reference sites) and on medians of log-transformed data from sampling sites]

	Selenium	Total dissolved solids	Evaporation index	Binary geologic variable
Selenium	**1.00**	0.45	–0.33	0.64
Total dissolved solids	0.45	**1.00**	0.20	0.33
Evaporation index	–0.33	0.20	**1.00**	–0.31
Binary geologic variable	0.64	0.33	–0.31	**1.00**

TDS concentration. EI and selenium correlated negatively ($r = -0.33$), however. EI is a poor predictor of the selenium potential without a significant local source of selenium in an area. The EI correlation coefficient likely shows the influence of samples from the Salton Sea area (*U*), which is a closed lake in a warm, dry climate having a high evaporation potential. Although imported water used for irrigation contains some selenium, no significant local geologic source of selenium is present in the area. At 8 μg/L, the 75th-percentile selenium concentration of surface-water samples from the Salton Sea area was comparatively low. By comparison, the 75th-percentile selenium concentration in samples from the middle Green River Basin (*N*), an area having a significant, local geologic source of selenium, was 73 μg/L. TDS concentration is a better indicator of evaporative effects on selenium concentrations than EI is at individual sampling locations. TDS concentration indicates how evapoconcentrated a sample actually is and reflects local and temporal conditions, whereas EI indicates only the potential for evapoconcentration in a region. Finally, because TDS and EI correlated positively ($r = 0.20$; $p = .0001$), use of both in a regression model could result in multicolinearity problems. For modeling purposes, TDS concentration alone was assumed to contain sufficient climatic information to predict the selenium potential of surface water in semiarid to arid settings.

The fundamental assumption of logistic regression is that the natural logarithm of the odds ratio (probability of being in a response category) is linearly related to the explanatory variables (Afifi and Clark, 1996). Logistic-regression model-fitting criteria used in this study included the Akaike Information Criterion, the percentage correct responses, model sensitivity, and the partial-likelihood ratio. The Akaike Information Criterion measures model error and includes a penalty for too many variables (Helsel and Hirsch, 1992). The smaller the Akaike Information Criterion, the better the model. The percentage correct responses and model sensitivity are based on comparison of observed selenium levels and selenium responses predicted by the logistic-regression model. An exceedance is defined herein as a surface-water selenium concentration greater than the USEPA chronic criterion of 5 μg/L. The proportion of correct responses is the sum of the number of observed exceedances correctly predicted by the model as exceedances and the number of observed nonexceedances correctly predicted as nonexceedances divided by the sum of observed exceedances and nonexceedances. Model sensitivity is the number of observed exceedances correctly predicted as exceedances divided by the number of observed exceedances. Higher values of these two criteria indicate better models.

The partial-likelihood ratio is used to compare nested models to determine the significance of adding one or more new variables to a model (Helsel and Hirsch, 1992). A nested model contains all explanatory variables in the original model plus one or more additional explanatory variables. Nonnested models have the same number of explanatory variables. If the partial-likelihood ratio is greater than the value of a chi-square distribution having degrees of freedom equal to the number of additional variables in the new model, then the more complex model is significantly improved over the original.

Logistic-regression models were screened for different data sets: local surface-water sites, all seasons (327 sites); local and main-stem surface-water sites, all seasons (379 sites); and local sites, spring and summer only (276 sites). Reference sites were excluded from the logistic-regression models.

Nested logistic-regression models developed by using data from local surface-water sites were compared. In nested models, a single new variable is added at each step (table 25). Performance criteria for model 2 indicated that significant improvement resulted from addition of the BGV. The percentage of correct responses improved from 67.0 to 84.4, and model sensitivity improved from 29.4 to 80.7 percent, compared to model 1, which had only TDS as an explanatory variable for the local surface-water model. Positive regression coefficients for both explanatory variables indicated that selenium concentration increased with increasing TDS concentration and with the presence of Upper Cretaceous marine sedimentary deposits. Additionally, the model had a partial-likelihood ratio of 111.09, significantly greater than the theoretical chi-square value of 3.841 [significance level (a) = 0.05]. Similar improvement occurred between models 3 and 4, which included local and main-stem sampling sites, and between seasonal local models 5 and 6.

The all-season local model using variables TDS and BGV (model 2 in table 25) was considered optimal on the basis of model-fitting criteria. Model 2 was more accurate than its seasonal counterpart (model 6) and had greater sensitivity than the version that included main-stem sites (model 4). However, model 4, which was just as accurate and nearly as sensitive as model 2, reliably predicted the likelihood of selenium contamination of large (main-stem) and small (local) streams, regardless of season, and was considered more robust because it had wider applicability.

The following equation for predicting the probability of exceeding the USEPA chronic criterion was produced by logistic regression (Afifi and Clark, 1996):

$$p = e^{\mathrm{logit}(p)} \div (1 + e^{\mathrm{logit}(p)}) , \qquad (2)$$

where p is the probability of exceeding the USEPA chronic criterion; and
e is the base of the natural logarithms having the approximate value of 2.71828.

Logit(p) is calculated by substituting the regression coefficients (table 25) into the following equation:

$$\mathrm{logit}(p) = \alpha + [\beta_1 \times \log_{10}(TDS)] + [\beta_2 \times (BGV)] , \qquad (3)$$

where α , β_1 and β_2 are regression coefficients;
TDS is total dissolved solids, in milligrams per liter; and
BGV is the binary geologic variable, which has a value of 0 or 1.

For model 2, if Cretaceous sedimentary rocks are present, equation 3 simplifies to equation 4 :

$$\mathrm{logit}(p) = 1.6629 \times \log_{10}(TDS) - 4.184 . \qquad (4)$$

If Cretaceous sedimentary rocks are not present, equation 3 simplifies to equation 5:

$$\mathrm{logit}(p) = 1.6629 \times \log_{10}(TDS) - 7.2647 . \qquad (5)$$

Logistic-regression results for model 2 are shown in figure 34, from which the probability that selenium concentrations exceed the chronic criterion for selenium may be estimated. The two following examples show how the regression equations are used to estimate probability.

For a site in an area where Upper Cretaceous marine sedimentary deposits form the bedrock and the TDS is 1,000 mg/L, the probability that the selenium concentration exceeds the USEPA chronic criterion is calculated from equations 2 and 4 (based on model 2). In this case, $\log_{10}(TDS) = 3.000$ and from equation 4 logit(p) = 0.805. By substituting this value for logit(p) into equation 2, probability can be calculated: p = 0.691. This value indicates an approximately 69-percent probability that the selenium concentration in the water exceeds 5 µg/L.

Given the same TDS (1,000 mg/L) in an area where Upper Cretaceous marine sedimentary rocks do not form the bedrock, the probability that the selenium concentration exceeds the USEPA chronic criterion is calculated from equations 2 and 5. As in the first case, $\log_{10}(TDS) = 3.000$, but in this second case, logit(p) = -2.276. By substituting this value for logit(p) into equation 2, probability can be calculated: p = 0.093, or about 9 percent.

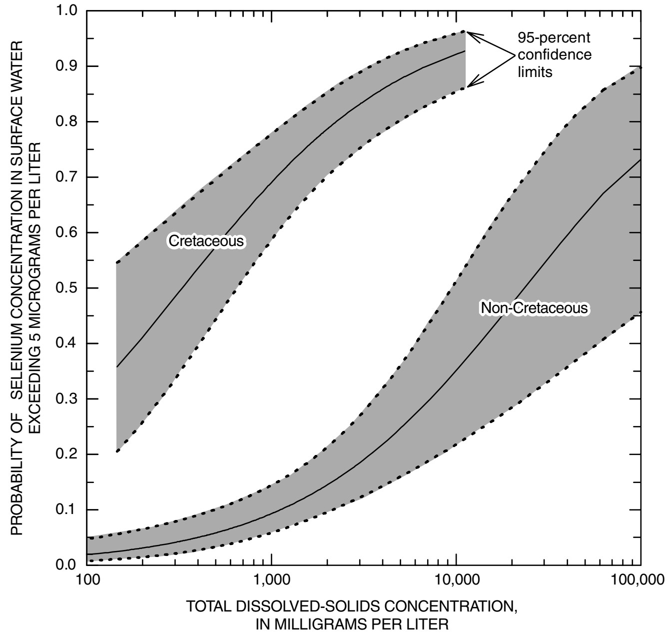


FIGURE 34. Relation between total dissolved-solids concentration and probability that selenium concentration exceeds 5 micrograms per liter (U.S. Environmental Protection Agency (1987) chronic criterion for selenium). Results based on model 2.

TABLE 25. *Results of logistic-regression modeling of selenium in surface-water samples from National Irrigation Water Quality Program study areas*

[Based on medians of log-transformed selenium and total-dissolved-solids data from local and mainstem sampling sites (excluding reference sites). Symbol: —, not applicable]

Model number	Explanatory variables	Number of observations[1]	Regression coefficients			Partial-likelihood ratio[2]	Correct responses (percent)	Model sensitivity[3] (percent)
			α	β_1	β_2			
Local sites, all seasons								
1	Total dissolved solids	327	–6.9510	2.0345	0	—	67.0	29.4
2	Total dissolved solids and binary geologic variable	327	–7.2647	1.6629	3.0807	111.093	84.4	80.7
Local and main-stem sites, all seasons								
3	Total dissolved solids	379	–7.3544	2.1636	0	—	68.1	29.5
4	Total dissolved solids and binary geologic variable	379	–8.4961	2.0492	2.7709	103.911	84.7	78.7
Local sites, spring and summer only								
5	Total dissolved solids	276	–7.9041	2.3472	0	—	71.0	46.9
6	Total dissolved solids and binary geologic variable	276	–8.8008	2.0962	3.0749	90.032	83.7	83.7

[1] Median selenium concentrations at sampling sites.
[2] $\chi^2_{0.95,\,1} = 3.841$
[3] The number of observed exceedances correctly predicted as exceedances divided by the number of observed exceedances.

Logistic-regression models were validated by using a data set of simulated "unknowns" created by partitioning the local surface-water data set into halves. Model parameters developed by using half of the data set were used with the other (simulated-unknowns) half of the data to compute theoretical probabilities of exceeding the USEPA chronic criterion and then were compared to observed probabilities. The percentage of correct responses decreased only slightly, from 87.0 to 84.7 percent, for the simulated-unknowns data set compared to the other half of the data set; also, model sensitivity increased slightly, from 78.8 to 80.3 percent. Because the model performed well when using the simulated-unknowns data set, logistic regression seems capable of predicting the probability selenium concentrations will exceed 5 µg/L in unsampled irrigation-drainage areas having a semiarid to arid climate.

A limitation of the model is that it does not consider components of TDS and their relation to the association of TDS and selenium. Saline waters high in sulfate likely are high in selenium because the two elements are chemically similar and selenium substitutes for sulfur in many sulfide minerals. The Upper Cretaceous Panoche Formation of California was thought to be a source of selenium because of its high salt content. Seeps from the Panoche Formation, however, produce a saline water high in chloride but low in selenium (Presser, 1994a).

PREDICTION USING MAJOR-ION CHEMISTRY

A fourth predictive model and management tool was developed to aid in the identification and prediction of seleniferous areas. The input to this model is major-ion concentrations in surface-water samples. The model uses geochemical modeling, pattern-recognition analysis, and classification modeling techniques to develop a predictive tool for identifying areas having surface water that may pose a selenium hazard. Background information on the geochemical and statistical tools used in the predictive model, model development, and model application (Naftz, 1996a,b) are summarized in the following sections.

GEOCHEMICAL AND STATISTICAL TOOLS USED IN MODEL DEVELOPMENT

The geochemical tool used in model development was the computer program SNORM (Bodine and Jones, 1986); it was used in combination with the statistical tools of pattern-recognition analysis and classification modeling (Wold and Sjostrom, 1977; Wold and others, 1984; Meglen and Sistko, 1985; Meglen, 1988, 1990, 1991; Conny and Meglen, 1990). In combination, these tools provide a method to predict whether surface-water samples might contain selenium concentrations that exceed 3 µg/L, the criterion used for protection of wildlife.

The computer program SNORM (Bodine and Jones, 1986) transforms a standard water analysis (major-ion concentrations) into the normative salt assemblage and corresponding simple-salt concentrations. For each water sample, the 12 different simple-salts concentrations calculated by using the SNORM program represent the minerals or salts that would remain after complete evaporation of a water sample.

After the simple salts were calculated for each of the almost 2,000 NIWQP water samples, statistical tools were applied to the resulting simple-salts data matrix. These tools were used to identify the hydrochemical facies characteristic of samples having concentrations of selenium exceeding the predetermined screening level of 3 µg/L. The software package Pirouette (Infometrix, 1992) was used for pattern-recognition analysis and classification modeling of the simple-salts data. To aid in data interpretation and classification modeling, the statistical methods principal-components analysis and soft independent modeling by class analogy were applied.

CREATION OF CLASSIFICATION MODEL

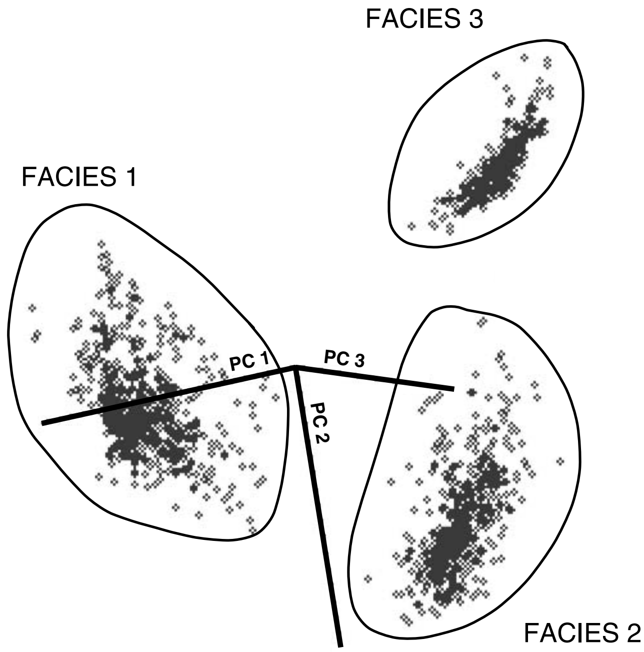
Salt norms were computed by using SNORM for 1,962 samples from 23 NIWQP study areas. Not all chemical analyses in the NIWQP data base could be used because SNORM requires complete chemical analyses. Because not all of the NIWQP surface-water samples were analyzed for major ions, only selected samples from the cumulative NIWQP data base could be used; analyses of samples from 3 of the 26 study areas (*B*, *K*, and *P*) did not qualify for inclusion.

The first step in developing the classification model was to determine if a specific combination of amounts and types of simple salts were correlated with selenium concentrations that exceed 3 µg/L. Selenium concentrations of 3 µg/L appear to be a toxicity threshold that can produce adverse effects in semiaquatic wildlife in lentic environments.

Three principal components best explained the simple-salts data set. The principal-components scores for the 1,962 water samples were plotted in three dimensions to evaluate the occurrence of distinct data clusters that could indicate common geochemical processes controlling surface-water chemistry in NIWQP study areas. The scores grouped into three distinct clusters, called facies 1, 2, and 3. The boundaries drawn around the clusters of principal-components scores aid in the visualization of the data (fig. 35) and indicate possible commonalities in geochemical processes.

The simple-salts association represented by facies 1 is most characteristic of water derived from the weathering of marine shales containing reduced and oxidized sulfur-bearing mineral phases. Because selenium commonly substitutes for sulphur in mineral structures, facies-1 water samples contain the most selenium, consistently exceeding 3 µg/L. The median selenium concentration for facies-1 samples is 10 µg/L compared to median values of 2 µg/L for facies 2 samples and less than 1 µg/L for facies 3 samples. A bivariate plot comparing the percentage of facies-1 water samples from each study area to the percentage of water samples having selenium concentrations of at least 3 µg/L (fig. 36) was used to confirm that facies-1 water samples contain selenium concentrations greater than or equal to 3 µg/L. For the 23 study areas, the percentage of facies-1 samples positively correlates with selenium concentrations of at least 3 µg/L ($r^2 = 0.77$, $n = 23$; fig. 36). In the Sun River area (*X*), for example, approximately 55 percent of the surface-water samples were classified as facies-1 and approximately 45 percent of the samples contained 3 or more µg/L of selenium.

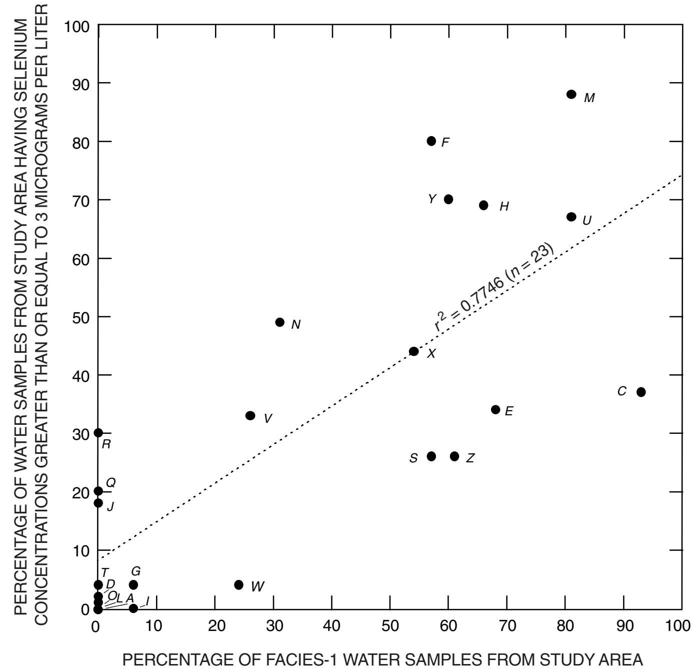
Pattern-recognition analysis of the simple-salts data calculated by the SNORM geochemical program indicated that selenium-producing areas could be identified on the basis of SNORM results. Soft independent modeling by class analogy (Wold and Sjostrom, 1977) was applied to the SNORM simple-salts data set (derived from NIWQP data) to construct a classification model that could be used to determine if sele-



EXPLANATION

Surface-water analysis

FIGURE 35. Three-dimensional principal-components scores plot showing grouping of water samples from National Irrigation Water Quality Program study areas into three distinct clusters. Scores based on principal-components (PC1, PC2, and PC3) analysis of simple-salts concentrations. Distinct clusters are classified as facies 1, 2, and 3.



EXPLANATION

Y ● **Data point for National Irrigation Water Quality Program study area**
Letter indicates study area

FIGURE 36. Relation between facies-1 water samples and water samples having selenium concentrations greater than or equal to 3 micrograms per liter, a guideline for protection of semi-aquatic wildlife (table 10). Letter identifies National Irrigation Water Quality Program study area (fig. 2).

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nium concentrations in surface water in the area are likely to exceed 3 µg/L. The training data set used to construct and optimize the classification model was a slightly modified version of the data set used in the pattern-recognition analysis of the NIWQP simple-salts data. This modified training data included data from 1,755 of the 1,962 samples collected in 23 study areas. Class assignments were consistent with the facies classification used during the pattern-recognition analysis. A 95-percent probability was used to define class inclusion. Specific parameters were evaluated during application of the soft independent modeling by class analogy to the training data set to ensure an optimal model for classification of the test data set. Two principal components were retained in each of the three classes, and the homogeneity of each class was ensured by visual inspection of the principal-components scores by class. Acceptable class separation during classification modeling of the training set was indicated by the residuals between classes and total modeling power (Naftz, 1996a).

APPLICATION OF CLASSIFICATION MODEL

The performance of the classification model was tested by using data from more than 2,000 samples of surface water from Wyoming and Utah compiled from the U.S. Geological Survey NWIS data base. Data from those two States were selected because of the variety of geologic settings represented and because of the documented presence of selenium in surface-water samples. The classification model was successful in identifying water samples having selenium concentrations of at least 3 µg/L; more than 75 percent of the samples from the test data set having such elevated selenium concentrations were classified in facies 1 and over 80 percent of the samples having selenium concentrations less than 3 µg/L were classified in facies 2 or 3. The demonstrated use of the classification model in differentiating samples that contained selenium from those that did not indicates that the model can be applied successfully to areas where selenium concentrations have not been determined.

Numerous circumstances contribute to the lack of selenium data for water samples. Examples of areas where selenium data are inadequate and where use of the classification model could be applied successfully include the following circumstances: (1) Selenium data were not collected. (2) Selenium data were collected, but the analytical reliability is questionable. (3) Selenium data were collected, but the detection level is high.

RECOMMENDATIONS FOR USE OF PREDICTIVE TOOLS

The following discussion presents recommendations on the best ways to apply the predictive tools described in this report. The section describes advantages and disadvantages of each method and how they can be used alone or in combination with other methods to help managers identify specific areas where selenium may be a problem.

Geochemical methods using major-ion chemistry are suitable for areas of the world where the principal geologic sources of selenium have not been identified or for parts of the United States where seleniferous rocks other than Upper Cretaceous sedimentary rocks are the soil-parent material for irrigated lands. Watersheds where selenium may be a problem are identified by a geochemical and statistical analysis of the results of water analyses for which selenium data were not collected. The major advantage of the method is that it depends only on the chemical nature of selenium, and thus no knowledge of the local geology or hydrology is needed. The major disadvantage is the high level of technical knowledge required to use the geochemical and statistical programs required by this method.

The maps identifying areas susceptible to irrigation-induced contamination (figs. 31 and 32) are specific to the Western United States. Their principal advantage is that the risk of selenium contamination in broad geographic regions can be evaluated quickly without the need to collect new information. Furthermore, land-use overlays can be created to aid Federal, State, and local water managers to evaluate whether areas for which they are responsible are susceptible to selenium contamination. Seiler and others (1999) presented maps that show locations of irrigated agricultural lands, BOR project areas, and National Wildlife Refuges in relation to susceptible areas. Disadvantages of the maps include the small scale at which they were produced, the lack of consideration of some hydrologic factors, and the specificity to the Western United States.

Like the susceptibility maps, the decision tree (fig. 33) is specific to the Western United States; however, unlike the maps, it can be modified easily. The principal advantages of using the decision tree are that it considers more of the factors that determine whether irrigation might cause contamination and that it ranks the likelihood that an area is or has the potential to be contaminated. Also, by slightly modifying the questions, the approach can be used in areas where seleniferous rocks other than those of Cretaceous age are known to be the soil-parent material. Disadvantages are that the decision tree is more time-consuming to use and using the decision tree requires more information about an area than is required for using the maps.

The logistic-regression method is most useful after a decision has been made that more sampling is warranted in an area. It is valuable in selecting sampling sites during an initial reconnaissance. After the applicability of the regression to a specific area has been determined, it can be used directly. Site-specific regressions also can be developed for use by wildlife managers; a site-specific regression could be used to manage a wetland unit on a real-time basis by obtaining dissolved-solids or specific-conductance values for it.

The most effective way to use the tools is in conjunction with each other. After preliminary identifications of susceptible areas are made using the maps, geochemical methods, or knowledge of the presence of seleniferous sedimentary deposits not of Cretaceous age, the decision tree can be used to further evaluate the risk of contamination.

Because these tools provide a cost-effective way to identify areas where irrigation is likely to cause selenium contamination, resources can be applied more efficiently to investigate those areas at highest risk. These tools, however, do not eliminate the need for site-specific evaluations to determine whether selenium contamination is in fact occurring, and if it is occurring, to what extent.

AVIAN-EGG RISK ASSESSMENT

ENVIRONMENTAL CONTAMINATION AND RISK ASSESSMENT

Water and sediment samples can be used to provide direct measures of environmental contamination and are essential for assessing ultimate sources of contamination. In the NIWQP study areas, selenium was the contaminant most frequently detected at elevated concentrations in surface water (table 11). Although the water and sediment data bases provide excellent documentation of contamination (or lack thereof), these environmental media provide only rudimentary measures of biotic risk. Risk is a function of exposure (Norton and others, 1992; Barnthouse, 1994), and the relation between levels of abiotic contamination and biotic exposure can be highly variable (Skorupa and Ohlendorf, 1991; Ohlendorf and others, 1993; Lemly, 1997b; Van Derveer and Canton, 1997). Therefore, biotic-exposure surveys are required for reliable toxicological-risk assessment (Keith, 1996).

The NIWQP biotic data base, summarized by taxa in table 9, provides an extensive basis for hazard assessment, the simplest form of risk assessment (Suter, 1993). Hazard assessment is categorical and consists primarily of comparing exposure data to hazard threshold points to determine whether a potential for hazard is or is not indicated (Lemly, 1996b). Reviews of toxic threshold points for selenium by Heinz (1996) and Lemly (1996c) provided relatively rigorous criteria for hazard assessment. Ideally such assessment is based on a broad array of environmental and biotic media; a protocol based on that principle was proposed by Lemly (1995, 1996a). Lemly's protocol uses a quantitative rating system, but ultimately it is a categorical hazard-assessment procedure. A high rating strongly indicates that a site should be categorized as hazardous, whereas a low score strongly indicates that a site should be categorized as safe. Lemly's protocol for rating the hazard posed at any given study site is a useful screening technique, but the ratings cannot be translated into direct estimates of toxic response.

The risk assessment presented here does not use the hazard-assessment approach for two reasons: First, most of the original NIWQP reconnaissance reports already have presented basic categorical assessments of hazard. Second, the biotic data base does not provide a consistent basis for applying a standard approach such as Lemly's protocol. Effort applied to sampling aquatic invertebrates, fish, and birds—the primary biotic media for Lemly's protocol—was uneven across NIWQP studies (table 9). Further, Lemly specifically identifies fish eggs as an ideal medium for hazard assessment, yet, eggs comprised only 0.7 percent of NIWQP's 2,410 fish tissue samples. By comparison, more than 50 percent of the 3,913 bird samples consisted of eggs.

More rigorous risk assessment, as opposed to simple hazard assessment, depends on quantitative techniques to estimate actual probabilities (or magnitudes) of toxic effect (for example, Bartell and others, 1992; Suter, 1993). The fundamental prerequisites for doing toxicological-risk assessment include (1) standardized and unbiased estimates of biotic exposure and (2) well-characterized exposure-response functions (Bartell and others, 1992; Burger and Gochfeld, 1992; Norton and others, 1992; Barnthouse, 1994; Solomon, 1996). The biotic components of the NIWQP studies were focused predominantly on surveying contaminant exposure. No systematic attempt was made by NIWQP biologists to collect data according to a standardized measure of toxic response.

Several studies included bioassay toxicity testing (Hallock and Hallock, 1993; Dileanis and others, 1996) or attempted to quantify precisely the rates of avian-embryo teratogenesis or mortality (Schroeder and others, 1988; See, Naftz, and others, 1992; Stephens and others, 1992; Nimick and others, 1996), but none of these studies produced statistically rigorous and broadly applicable exposure-response functions. Thus, although the NIWQP biotic data base provides a reasonable exposure survey, NIWQP-specific toxic-response functions were not developed. Long-term studies in the San Joaquin Valley initiated during the San Joaquin Valley Drainage Program, however, did include a large and systematically collected body of response data that, when supplemented with the sparse NIWQP response data, provides statistically rigorous and broadly applicable exposure-response functions for avian-embryonic exposure to selenium (Skorupa, 1998). Thus, NIWQP biotic-exposure data were combined with San Joaquin Valley Drainage Program toxic-response data to provide a quantitative toxicological-risk assessment consistent with the National Research Council (1993) standard of " * * * a probabilistic statement of the 'outcome' associated with an ecological receptor being exposed to some form of stress * * * ".

CHOICE OF RISK METRIC

Avian-embryonic exposure to selenium and response to that exposure, in the forms of teratogenesis and embryo viability, were the chosen risk metrics. Although this choice was dictated by the general lack of well-characterized toxic-response functions for other risk metrics, these risk metrics are also the most appropriate. In addition, NIWQP sampling plans intentionally focused on the collection of bird eggs (among other biota) because earlier studies at Kesterson had demonstrated the importance of evaluating embryo viability and the occurrence of terata.

Avian eggs (embryos) have several essential advantages over other biotic tissues for assessing risk. The sensitivity of amphibians and reptiles to aquatic selenium contamination simply is not known, thereby making those taxa inappropriate as a risk metric. Fish and birds are the two taxa of animals clearly most sensitive to aquatic selenium contamination (Ohlendorf, 1989; Lemly, 1996a,c; Skorupa, 1998); using less sensitive taxa, such as aquatic invertebrates or mammals, would be inappropriate as a risk metric. Of the various fish life-stages that could be sampled, embryonic and larval generally are considered to be the most sensitive; for birds, the embryonic life-stage is the most sensitive. Also, for both fish and birds, selenium-induced reproductive impairment is one of the most sensitive toxic endpoints (Heinz, 1996; Lemly, 1996c). As indicated in the previous section, the NIWQP biotic data base is nearly devoid of records for fish eggs but records for bird eggs are abundant.

The focus on bird eggs is not meant to imply that reproductive risks should be the sole source of concern for biotic effects in NIWQP study areas. Researchers concluded that for birds (Tully and Franke, 1935; Heinz and Fitzgerald, 1993), fish (Lemly, 1993a, 1996d), and mammals (Ghosh and others, 1993), the sensitivity of adults to selenium poisoning greatly increases during the winter as compared to more thermoneutral seasons of the year, such as the breeding season. Furthermore, immunobiological effects of selenium exposure eventually may prove to be the most sensitive of all toxic endpoints (Whiteley, 1989; Fairbrother and Fowles, 1990; Schamber and others, 1995). Unfortunately, field data quantifying the direct toxicity of selenium for nonbreeding fish and wildlife are rare. Indirect, immunobiologically mediated toxicity has not been studied sufficiently to provide a well-developed basis for either simple hazard assessment or quantitative risk assessment.

The other candidate risk metrics for the NIWQP biotic data base were whole-body analyses for fish and liver analyses for birds. Avian hepatotoxicity generally is considered inferior to avian embryotoxicity as a reliable toxic endpoint for selenosis (Heinz, 1996). Moller (1996) suggested that selenium may become elevated in bird livers either as an adaptive response to oxidative stress or by excessive dietary exposure to selenium. In the former instance, high concentrations of selenium in liver tissue are not indicators of toxicity, and in the latter instance they are. No comparable circumstances for producing "false positives" are known for selenium concentrations in avian eggs.

Avian eggs, as a risk metric, have much less potential than avian livers or whole-body fish residues to be compromised by survivor bias because reproductive impairment occurs at levels of exposure to selenium much less than the levels required to cause hen mortality (Heinz, 1996). Eggs containing dead or live embryos are equally likely to be sampled by biologists if eggs are collected at random from complete clutches. In other words, neither biologists nor incubating adult birds distinguish between eggs containing live or dead embryos. In addition, the egg provides a standardized embryonic exposure environment, an easily quantifiable exposure unit, a uniform age of initial exposure, a relatively uniform duration of exposure for eggs at comparable stages of incubation, and a standardized season of exposure. Therefore, for many reasons, avian eggs are clearly the optimal risk metric for the NIWQP biotic data base.

REASONS FOR FOCUS ON SELENIUM

Comprehensive field and laboratory research completed to determine the cause(s) of avian reproductive impairment at Kesterson National Wildlife Refuge led to the conclusion that selenium poisoning alone was sufficient to explain the congenital deformities and reproductive failure of waterfowl at Kesterson National Wildlife Refuge (Ohlendorf, Hoffman, and others, 1986; Heinz and others, 1989; Ohlendorf, 1989; U.S. Fish and Wildlife Service, 1990). The evidence for selenium poisoning was so strong that Suter (1993) referred to the Kesterson case study as one of just a few "gold standards" for establishing causation in a retrospective ecological-risk assessment. Thus, selenium was the primary contaminant of concern at Kesterson, and the Kesterson case provided the impetus for the NIWQP. The NIWQP, however, was a broad regional survey that possibly could turn up additional contaminant problems associated with irrigation and applicable to specific localities.

Authors of the NIWQP reconnaissance reports identified nine contaminants of greatest concern, including arsenic, boron, cadmium, copper, mercury, molybdenum, selenium, zinc, and DDT (U.S. Department of the Interior, 1998). Background levels and toxic threshold levels for avian eggs were compiled for arsenic, boron, cadmium, copper, mercury, molybdenum, selenium, zinc, and DDE (table 26). Selenium

TABLE 26. *Background levels and toxic thresholds for contaminants in avian eggs*

[Abbreviation and symbol: DW, Dry weight; —, not known.]

Constituent	Background level (µg/g DW)	Toxic threshold		Dose-response threshold
		No observed effect level	Lowest observed effect level	
Arsenic:				
Organic	[1]0.25	[2]1.3	[2]2.8	—
Inorganic	—	[3]1.8	[3]3.6	—
Boron	[1,4]1.0	[5]22	[5]38	—
Cadmium	[6]0.15	—	—	—
Copper	[7]5.5	—	—	—
Mercury	[8]0.1	—	—	[9]3.0
Molybdenum	[1]0.25	[10]23	33	—
Selenium	[11]1.9	—	—	[12]6.0
Zinc	[1,8]50	—	—	—
DDE[13]	[14]0.3	—	—	[14]3.7

[1] T.J. Kubiak (U.S. Fish and Wildlife Service, written commun., 1991), based on poultry data reported by Romanoff and Romanoff (1949).

[2] Based on poultry data (Evans and others, 1953; Moore and others, 1954).

[3] Based on sodium arsenate data for mallards (Stanley and others, 1994).

[4] Unpublished field data for ducks and shorebirds sampled at reference sites in San Joaquin River Basin (R.L. Hothem and D.P. Welsh, U.S. Fish and Wildlife Service, written commun., 1990) and Tulare Basin (U.S. Fish and Wildlife Service, unpublished data) in California.

[5] Based on data for mallards (Stanley and others, 1996).

[6] Based on poultry data (Leach and others, 1979).

[7] Based on poultry data (Puls, 1988) and waterfowl data (Haseltine and others, 1980).

[8] Based on poultry data (Puls, 1988).

[9] Based on data for mallards (Heinz, 1979).

[10] Based on poultry data (Lepore and Miller, 1965).

[11] Based on waterbird data (Skorupa and Ohlendorf, 1991).

[12] Based on black-necked stilts field data (Skorupa, 1998).

[13] Concentrations are in µg/g wet weight.

[14] Based on avian data from Blus (1996).

was overwhelmingly the most often identified constituent of concern, being named in 15 of the 26 reconnaissance reports. Other constituents of concern were identified in fewer reconnaissance reports (generally six to nine reports). The tabulated toxic-exceedance rates for each contaminant of greatest concern in each study area clearly show that selenium is the most prevalent of the hazardous constituents associated with irrigation in the Western United States, as sampled by the NIWQP (table 27). For all NIWQP contaminants of greatest concern, except selenium and DDE, the median toxic exceedance rate for the sampled study areas ($n = 23$) was 0. For the NIWQP contaminants of greatest concern, except mercury, selenium, and DDE, the maximum rates of toxic exceedance across the sampled study areas were less than 2.2 percent. Thus, for avian eggs, the only contaminants potentially warranting regional-level risk assessment are mercury, selenium, and DDE.

Although 7 of the 26 NIWQP study areas yielded one or more avian eggs exceeding the hazard threshold for mercury (3 μg/g), the highest exceedance rate was only 10.6 percent. The maximum individual value observed in any study area, 8.5 μg/g mercury, was less than three times the hazard threshold. Therefore, the mercury profile is best described as a few eggs, only slightly exceeding the hazard threshold, in about one-fourth of the study areas sampled. By contrast, 15 study areas yielded one or more avian eggs exceeding the hazard threshold for selenium (6 μg/g), and three areas had exceedance rates greater than 80 percent. The maximum individual value of 160 μg/g selenium was more than 25 times the hazard threshold. Clearly, selenium was a much more dominant contaminant of concern than mercury in the NIWQP study areas (table 27).

TABLE 27. *Toxic exposures of contaminants to avian eggs from National Irrigation Water Quality Program study areas*

[Symbol: —, not analyzed.]

Study area		Toxic exceedance[1] (percent)								
Identifier[2]	Name	Arsenic	Boron	Cadmium	Copper	Mercury	Molybdenum	Selenium	Zinc	DDE
A	American Falls Reservoir, Idaho	0	—	—	0	7.7	—	0	0	23.1
B	Angostura Reclamation Unit, South Dakota	0	0	0	0	0	0	0	0	0
C	Belle Fourche Reclamation Project, South Dakota	0	0	0	0	0	0	40.0	0	0
D	Columbia River Basin, Washington	0	—	—	—	0	—	0	0	3.4
E	Dolores–Ute Mountain area, Colorado	0	0	0	0	0	0	13.3	0	0
F	Gunnison River Basin–Grand Valley Project, Colorado	0	0	0	0	0	0	84.6	0	12.5
G	Humboldt River area, Nevada	0	0	0	0	0	0	0	0	—
H	Kendrick Reclamation Project, Wyoming	0	0	.3	.3	.3	0	89.7	0	4.0
I	Klamath Basin Refuge Complex, California–Oregon	0	0	—	0	0	0	0	0	12.7
J	Lower Colorado River valley, California–Arizona	—	—	—	—	—	—	—	—	—
K	Lower Rio Grande valley, Texas	—	—	—	—	—	—	—	—	—
L	Malheur National Wildlife Refuge, Oregon	2.1	0	0	0	10.6	0	0	0	30.0
M	Middle Arkansas River Basin, Colorado–Kansas	0	0	0	0	0	0	66.7	0	0
N	Middle Green River Basin, Utah	.6	0	0	.3	.3	0	48.0	0	0
O	Middle Rio Grande, New Mexico	0	0	0	0	0	0	0	0	0
P	Milk River Basin, Montana	0	0	0	0	0	—	0	0	0
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	0	0	0	0	5.3	0	0	0	0
R	Pine River area, Colorado	0	0	0	0	0	—	21.7	0	0
S	Riverton Reclamation Project, Wyoming	0	0	—	0	0	0	46.7	0	0
T	Sacramento Refuge Complex, California	0	—	—	0	0	—	5.0	0	10.5
U	Salton Sea area, California	0	0	0	0	0	0	11.7	0	38.8
V	San Juan River area, New Mexico	0	0	0	0	0	0	7.7	0	—
W	Stillwater Wildlife Management Area, Nevada	1.1	0	0	0	4.3	0	40.2	0	—
X	Sun River area, Montana	.4	.7	0	0	.7	0	30.3	0	8.3
Y	Tulare Lake Bed area, California	0	0	0	0	0	0	91.7	0	0
Z	Vermejo Project area, New Mexico	—	—	—	—	—	—	—	—	—
	Median	0	0	0	0	0	0	11.7	0	3.4
	Maximum	2.1	.7	.3	.3	10.6	0	91.7	0	38.8

[1] Relative to no observed effect level (table 26). For constituents without well established toxicity guidelines (cadmium, copper, and zinc), exceedance was relative to ten times the normal background level.

[2] Used in figure 2 to show locations of study areas.

Although DDE appears to pose a greater hazard than mercury in the NIWQP study areas, it is nonetheless still of much less regional concern than is selenium. A separate risk assessment for DDE is beyond the scope of this report. Additionally, because of DDE's high degree of persistence in avian tissues (Blus, 1996), it is a less appropriate focal contaminant for risk analysis than is selenium. Hen exposure to DDE as reflected in the data for birds' eggs may have occurred outside the NIWQP study areas, whereas selenium exposure as documented in the egg data set is unlikely to have occurred outside the study areas (Heinz, 1993, 1996).

In summary, the reasons for focusing on selenium in this risk assessment include the well-documented causative linkage between selenium and the avian reproductive impairment at Kesterson National Wildlife Refuge, the widespread occurrence of waterborne selenium contamination in the NIWQP study areas (table 15), the dominant position of selenium as a contaminant of concern in eggs from NIWQP study areas (table 26), and selenium's differential propensity (compared to DDE) to reflect localized contaminant conditions.

TERATOGENIC-RISK ASSESSMENT

Selenium is a well-documented causative agent for avian teratogenesis (Franke and Tully, 1935, 1936; Gruenwald, 1958; Hoffman and Heinz, 1988; Hoffman and others, 1988). Therefore, the incidence of deformed embryos is a response variable that can be used to assess biotic effects of environmental selenium exposure. However, to precisely define what is being counted as a teratogenic response is important when addressing the issue of avian teratogenesis. Measured incidences of teratogenesis depend on what types of abnormalities are included under the umbrella of terata, or malformations, or deformities. Results also depend on an investigator's method of examining specimens for abnormalities.

Herein, teratogenesis refers to the incidence of irreversible major structural deformities that are overtly obvious upon superficial external inspection of an avian embryo. Lemly (1993c, 1997a) presented comparable criteria for fish larvae. Teratogenic response as used here was described in such terms as "monstrosities" in early scientific literature (Franke and Tully, 1936; Franke and others, 1936). In practice in the NIWQP studies, major deformities of the eyes, bill, or limbs were almost the only criteria used for qualifying terata. Nonstructural abnormalities, even though externally visible, such as hydrocephaly, generalized edema, subcutaneous hemorrhaging, and cloudy eyes did not qualify as teratogenic responses for the assessments discussed here. Deformities of organs or other internal soft tissues also were not included.

The intentionally conservative definition of teratogenesis used herein includes only the most pronounced and easily identified types of terata. This is done for two reasons: First, by these criteria, observers having highly variable levels of experience can examine sets of avian embryos and produce highly consistent and comparable assessments of teratogenic response. These selenium-caused "monstrosities" are not normally a matter of observer interpretation; they obviously exist (fig. 37) or do not. Second, only counting pronounced forms of terata eliminates the more general types of embryonic abnormalities that have multiple potential sources of causation (O'Toole and Raisbeck, 1998). Eliminating such abnormalities from the definition of teratogenic response was expected to reduce at least some of the background noise that could obscure the selenium-induced teratogenic-response curve. As a combined suite, alternative causes are few for the severe multiple, overt, structural deformities of the eyes, bill, and limbs that are typical of selenium poisoning (fig. 37; Franke and Tully, 1935; Ohlendorf, Hoffman, and others, 1986; Presser and Ohlendorf, 1987; Hoffman and Heinz, 1988; Hoffman and others, 1988; Ohlendorf and others, 1988; Howard, 1989; Ohlendorf, 1989; Bobker, 1993; Ohlendorf and Hothem (1995); Ohlendorf, 1996; O'Toole and Raisbeck, 1998). The spatulate narrowing of the upper bill (beak) and hypoplasia (reduction) of the lower bill in embryos (fig. 37) is reported to be a "distinctive feature" of selenium-induced teratogenesis among ducks (O'Toole and Raisbeck, 1998). Among shorebirds, such as stilts and avocets, characteristic features of selenium-induced teratogenesis include absence of eyes, malformation of the bill and limbs, and in the most severe cases, exencephaly.

The characteristics of terata that might be caused by other common contaminants in NIWQP areas are distinct from those caused by selenium. In mallards, external applications of 1 mg of methylmercury per egg caused minor skeletal aberrations and incomplete ossification (Hoffman and Moore, 1979). Higher doses caused micromelia (abnormally small and malformed extremities), gastroschisis (congenital opening of the ventral abdominal wall), and eye and brain defects. No terata were detected in chicks or dead embryos following separate injections of DDT, DDD, and DDE into chicken eggs, although typical DDT neurological poisoning symptoms were observed (Abou-Donia and Menzel, 1968). Detailed descriptions of avian terata induced by maternally delivered arsenic have not yet been reported in the scientific literature because even unrealistically high dietary dosing of hens has not induced sufficient rates of teratogenesis for detailed characterization. At the concentrations measured in eggs at NIWQP sites, arsenic is functionally nonteratogenic (Evans and others, 1953; Moore and others, 1954; Stanley and others, 1994).

Teratogenesis, especially when conservatively defined, is a relatively insensitive response variable for selenium poisoning. For example, Stanley and others (1996) studied the reproductive performance of captive game-farm mallards fed selenium-treated diets and found a 34-percent depression in egg hatchability even though the dietary selenium treatment (7 mg/kg as

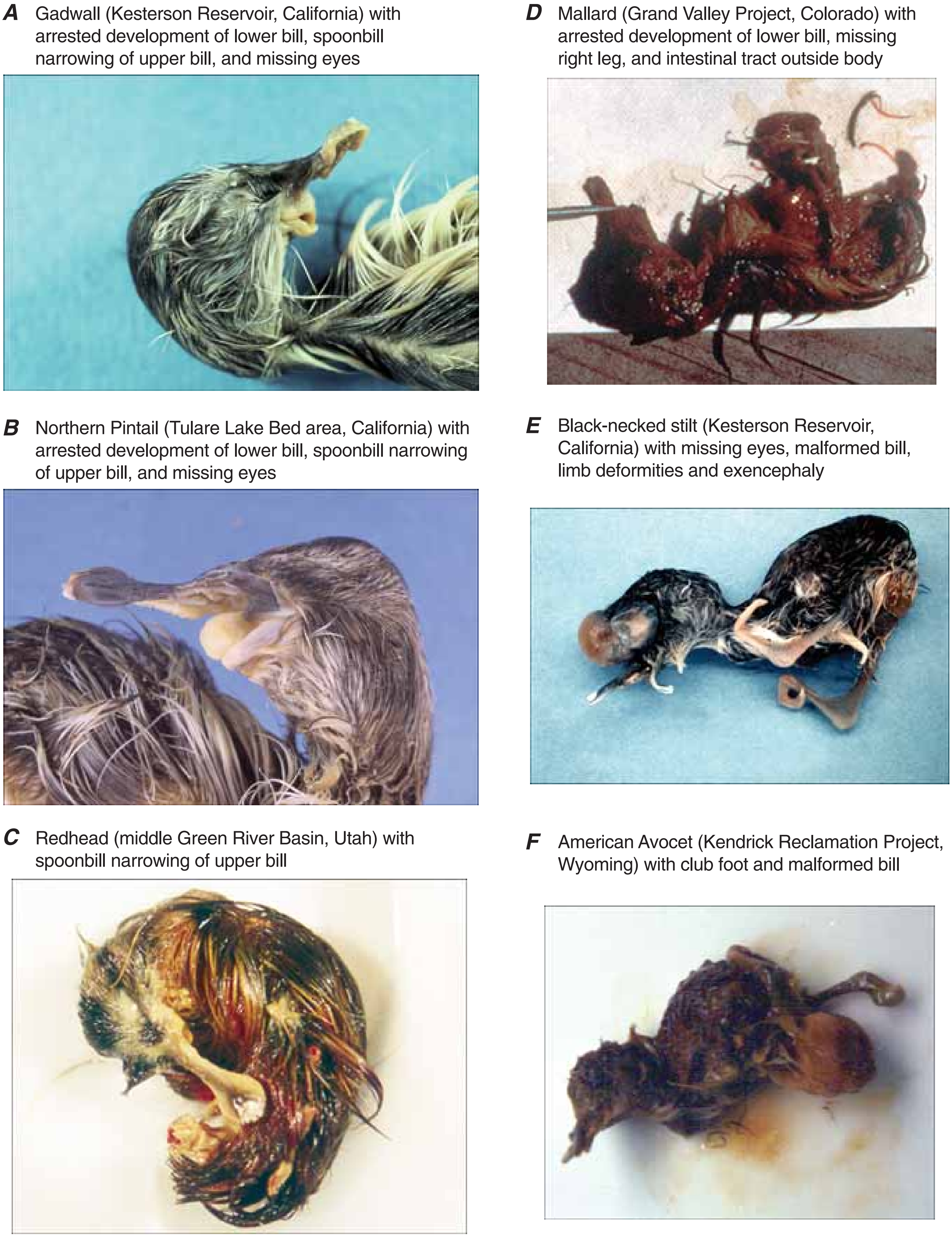


FIGURE 37. Typical selenium-induced terata of avian embryos.

selenomethionine) was not sufficient to induce embryo teratogenesis. Although estimates of teratogenesis thresholds are conservative measures of threshold points for reproductive effects, teratogenesis as a response variable is much easier to measure in the field than egg hatchability. Teratogenesis assessments can be made by collecting eggs during one visit, assessing the status of the embryos inside the collected eggs, and chemically analyzing the egg contents (including the embryo). To relate egg hatchability to egg chemistry requires the marking of nests, collection of a sample egg from each nest, and multiple return visits to find each nest and monitor the fate of the sibling eggs that were left in the nest at the time the sample eggs were collected. Even then, only the data from nests incubated to full term are useful. Given the typical rates of nest predation, nest flooding, and nest abandonment (Ohlendorf and others, 1989; Hothem and Welsh, 1994b), an observer may have to monitor a ratio of 5 to 10 nests for every usable full-term nest record. Therefore, field assessments of egg viability (hatchability) as a function of egg chemistry are much less frequently attempted than teratogenesis assessments.

MULTIELEMENT TERATOGENIC-RESPONSE DATA

Subsurface irrigation-drainage water commonly contains elevated concentrations of a diverse assemblage of potential inorganic contaminants. For example, San Joaquin Valley Drainage Program investigators designated 10 inorganic constituents to be of primary or probable concern and an additional 10 inorganic constituents to be of possible concern (San Joaquin Valley Drainage Program, 1990). Many of the other NIWQP study areas also were contaminated by multiple trace elements. Some trace elements, including cadmium and uranium, are poorly transferred to avian eggs regardless of a hen's dietary exposure (Haseltine and Sileo, 1983; Robinson and others, 1984; Ohlendorf, 1993) and therefore could not cause an embryonic response. Other constituents, such as boron, are readily biotransferred to avian eggs (Ohlendorf, Hoffman, and others, 1986; Smith and Anders, 1989; Ohlendorf and others, 1993; Setmire and others, 1993; Stanley and others, 1996). Therefore, even though captive-feeding trials demonstrated that selenium alone was sufficient to explain the avian teratogenesis observed at Kesterson (Heinz and others, 1987, 1989), at least some uncertainty has remained as to whether constituents other than selenium also were playing a role (in addition to or in conjunction with selenium) in causing the avian teratogenesis associated with irrigation-induced aquatic contamination. This uncertainty has persisted partly because a direct multielement evaluation of field data has never been presented.

Such a direct multielement evaluation can only be completed on sets of avian eggs that meet strict criteria for random sampling in the field, and random selection for chemical analysis. (In a typical study, more eggs are sampled in the field than are eventually chemically analyzed.) In addition, the eggs should come from sites having reasonably high rates of embryo teratogenesis, and they should all have assessable embryos (eggs in a stage of development sufficiently advanced that the occurrence of teratogenesis can be determined readily). The eggs should be analyzed for a diverse spectrum of inorganic constituents. Finally, to avoid having chemical associations masked by potentially large intersite variability in rates of teratogenesis, a direct multielement evaluation should be restricted to samples from different sites having comparably high rates of teratogenesis. Therefore, the data set selected for multielement evaluation consisted of samples collected from two sites within the Tulare Lake Bed area (*Y*) that met all these conditions.

During 10 years of study in the Tulare Lake Bed area (*Y*) and surrounding parts of the San Joaquin Valley in California, more than 1,900 avian eggs were collected and chemically analyzed (U.S. Fish and Wildlife Service, unpublished data). A subset of 32 black-necked stilt eggs (22 normal and 10 deformed embryos) from two sampling sites met the criteria for a direct multielement evaluation of field data for chemical associations with embryo teratogenesis. This subset of stilt eggs is referred to herein as the Tulare multielement-response sample.

Eggs in the Tulare multielement-response sample were analyzed for 17 inorganic constituents by inductively coupled plasma-emission spectroscopy. The constituents analyzed included aluminum, barium, beryllium, boron, cadmium, chromium, copper, iron, lead, magnesium, manganese, mercury, molybdenum, nickel, selenium, strontium, vanadium, and zinc. Only for barium, boron, copper, iron, magnesium, manganese, mercury, selenium, strontium, and zinc were the levels of contamination sufficiently high or the analytical limits of detection sufficiently low for at least 70 percent of the samples to contain quantifiable amounts of the chemical constituent. Univariate comparisons of the chemical profiles for eggs containing normal and deformed embryos are presented for those constituents in figure 38. The few values that were below detection limits were estimated to be one-half of the applicable detection limit.

Selenium shows the strongest separation of profiles (fig. 38*H*); as expected, eggs exhibiting deformity contained significantly greater selenium (Student's $t = 3.64$; $p = 0.001$). Eggs exhibiting deformities also contained significantly greater boron (fig. 38*B*), and magnesium (fig. 38*E*) concentrations; however, the concentrations of these constituents significantly covary with selenium concentrations ($p < 0.1$; table 28). Because elements that significantly covary with boron and magnesium but not with selenium (such as barium and zinc) did not show significant differences in concentration profiles for normal eggs and eggs exhibiting deformity (figs. 38*A, J*), it seems likely that the significant univariate-profile differences observed for boron and magnesium are artifacts of their covariation with selenium. That boron is not a causative agent for avian teratogenesis and does not interact with selenium has been established empirically (Smith and Anders, 1989; Stanley and others, 1996). Likewise, direct or interactive teratogenic effects are not expected from magnesium (Birch, 1988).

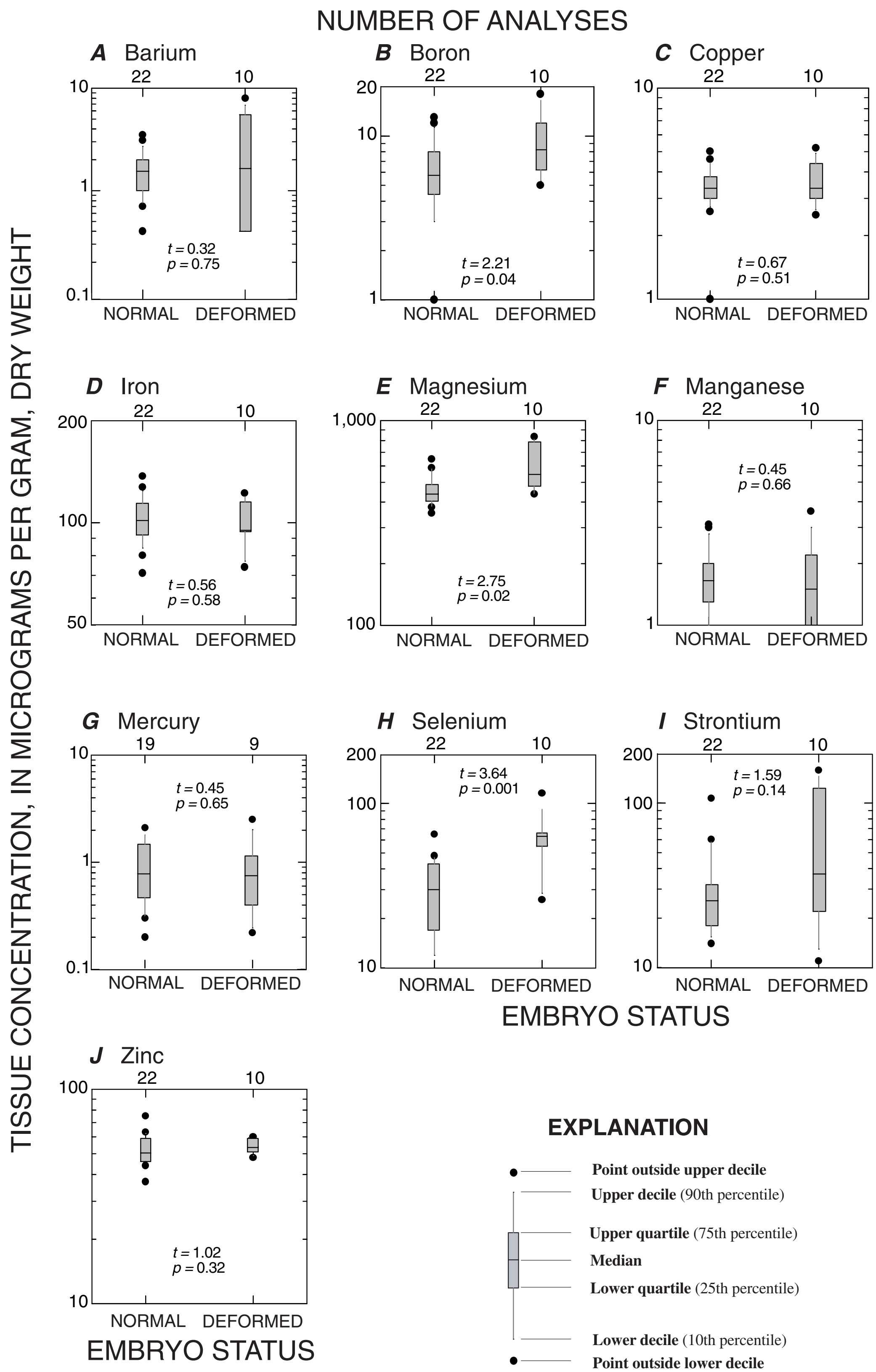


FIGURE 38. Comparison of trace-element concentrations in stilt eggs containing normal and deformed embryos. *t*, student's *t* statistic; *p*, probability of the two populations being the same based on Student's *t* test.

TABLE 28. *Correlation matrix for Tulare Lake Basin multi-element-response sample*

[All tabulated values are *p*-values or significance levels for each bivariate correlation; smaller absolute values indicate stronger correlation. Correlations are based on log-transformed data. Symbols: —, no significant correlation ($p > 0.10$); <, less than]

Variable	Barium	Boron	Copper	Iron	Magnesium	Manganese	Selenium	Strontium	Zinc
Barium	**0.000**	–0.013	—	—	0.043	0.004	—	<0.001	—
Boron	–0.013	**0.000**	—	—	—	—	0.064	—	—
Copper	—	—	**0.000**	0.003	—	—	—	—	0.072
Iron	—	—	0.003	**0.000**	—	—	—	—	0.099
Magnesium	0.043	—	—	—	**0.000**	—	0.009	<0.001	0.001
Manganese	0.004	—	—	—	—	**0.000**	—	0.020	—
Selenium	—	0.064	—	—	0.009	—	**0.000**	0.003	—
Strontium	<0.001	—	—	—	<0.001	0.020	0.003	**0.000**	0.097
Zinc	—	—	0.072	0.099	0.001	—	—	0.097	**0.000**

Although eggs exhibiting deformity contained greater concentrations of strontium, the difference was not statistically significant (fig. 38*I*; $p = 0.14$). Even if the association between strontium and terata were significant, strontium would be an unlikely cause of the observed deformities. Although strontium is teratogenic when injected into poultry eggs, it is not teratogenic even at concentrations where 100 percent of the embryos are dying when eggs received the strontium through the maternal diet (Mraz and others, 1967). Like boron and magnesium, strontium also strongly covaried with selenium (table 28).

Exploratory factor analysis (Afifi and Clark, 1996) was applied to clarify the association of inorganic constituents in the eggs with each other and the presence of embryonic terata. Because all constituents are considered simultaneously in this analysis, the potential for site associations and chemical associations getting confounded is greatly reduced. Thus, compared to the univariate profiles ($n = 32$), data from more sites were available for analysis and a slightly larger subset ($n = 83$) of the Tulare multielement-response sample eggs could be used. The results of this analysis (fig. 39) clearly show that the association between selenium and terata is much tighter than the association between boron, magnesium, strontium, and terata. Arsenic and mercury were not analyzed for all of the eggs and therefore could not be included in the exploratory factor analysis which requires complete data sets.

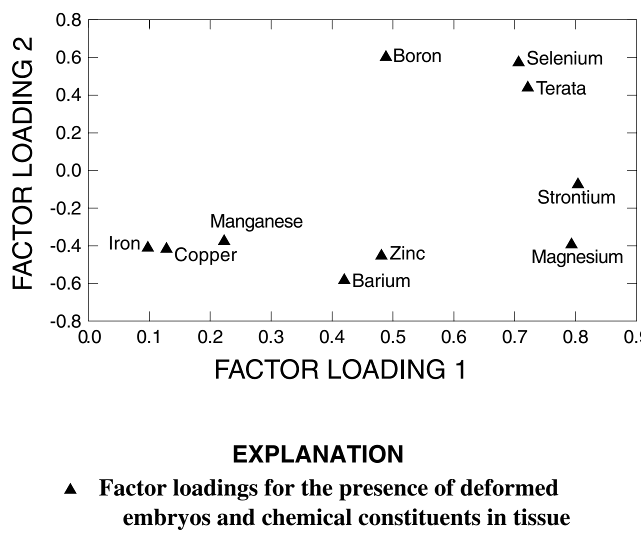


FIGURE 39. Exploratory factor-analysis loadings, showing association of trace elements in eggs and the presence of terata. Based on data for black-necked stilt eggs from Tulare Lake Bed area in California (Schroeder and others, 1988; Ohlendorf and others, 1993; U.S. Fish and Wildlife Service, unpublished data).

RELEVANCE OF ARSENIC AND MERCURY

Arsenic and mercury are known agents of avian teratogenesis and both are known to interact with selenium (Stanley and others, 1994; Heinz and Hoffman, 1998). Although neither was included in the inductively coupled plasma-emission-spectroscopy scans of the Tulare multielement-response-sample eggs, both were analyzed by other methods in subsets of those sample eggs. For arsenic, a subset was analyzed by hydride-generation atomic-absorption spectrophotometry, and for mercury, by cold-vapor atomic-absorption spectrophotometry. (These sample subsets analyzed for arsenic and mercury overlapped only minimally with the subsets analyzed for other constituents by inductively coupled plasma-emission spectroscopy.)

Fewer than 1 percent of all eggs analyzed exceeded the 0.4-µg/g detection limit for arsenic, and normal background is about 0.1 to 0.4 µg/g (Romanoff and Romanoff, 1949). Arsenic analyses consistently show that eggs having detectable concentrations of arsenic are extremely rare (Ohlendorf and others, 1993). The maximum arsenic concentration recorded for the Tulare Lake Bed area (*Y*) was only 1.8 µg/g (Ohlendorf and others, 1993), an amount that would have a low probability of inducing teratogenesis directly and that, in combination with selenium, actually would suppress the incidence of teratogenesis (Stanley and others, 1994). For these reasons, teratogenic effects from embryonic exposure to arsenic are unlikely.

Likewise, exposure to mercury in the egg was minimal (although detectable) in the Tulare Lake Bed area (*Y*) and in the upper San Joaquin Valley. Among 78 stilt eggs analyzed for mercury, the maximum observed concentration of 2.5 µg/g (U.S. Fish and Wildlife Service, unpublished data) is less than the known thresholds for direct or interactive teratogenic effects (3 µg/g; Heinz and Hoffman, 1998). A subset of 28 black-necked stilt eggs that met the criteria for univariate comparison did not exhibit any significant difference in the mercury-concentration profiles for normal eggs versus eggs exhibiting deformities (fig. 38*G*). This, too, suggests that the possibility of teratogenic effects from embryonic exposure to mercury is unlikely.

For 11 of the 26 NIWQP study areas, available stilt and avocet data was directly comparable to the stilt data from the Tulare Lake Bed area (*Y*) and the upper San Joaquin Valley. Mercury profiles for stilt and avocet eggs from these 11 NIWQP study areas suggest that direct or interactive teratogenic effects of mercury are unlikely throughout the NIWQP study areas (fig. 40). Mercury was not associated with deformities in the Tulare Lake Bed area (*Y*; fig. 38*G*), and the great majority of the mercury concentrations from the NIWQP areas were less than the median mercury concentration in that area (fig. 40). Furthermore, only one sample from the 11 NIWQP study areas had a mercury concentration exceeding 3 µg/g, the known threshold for direct or interactive teratogenic effects.

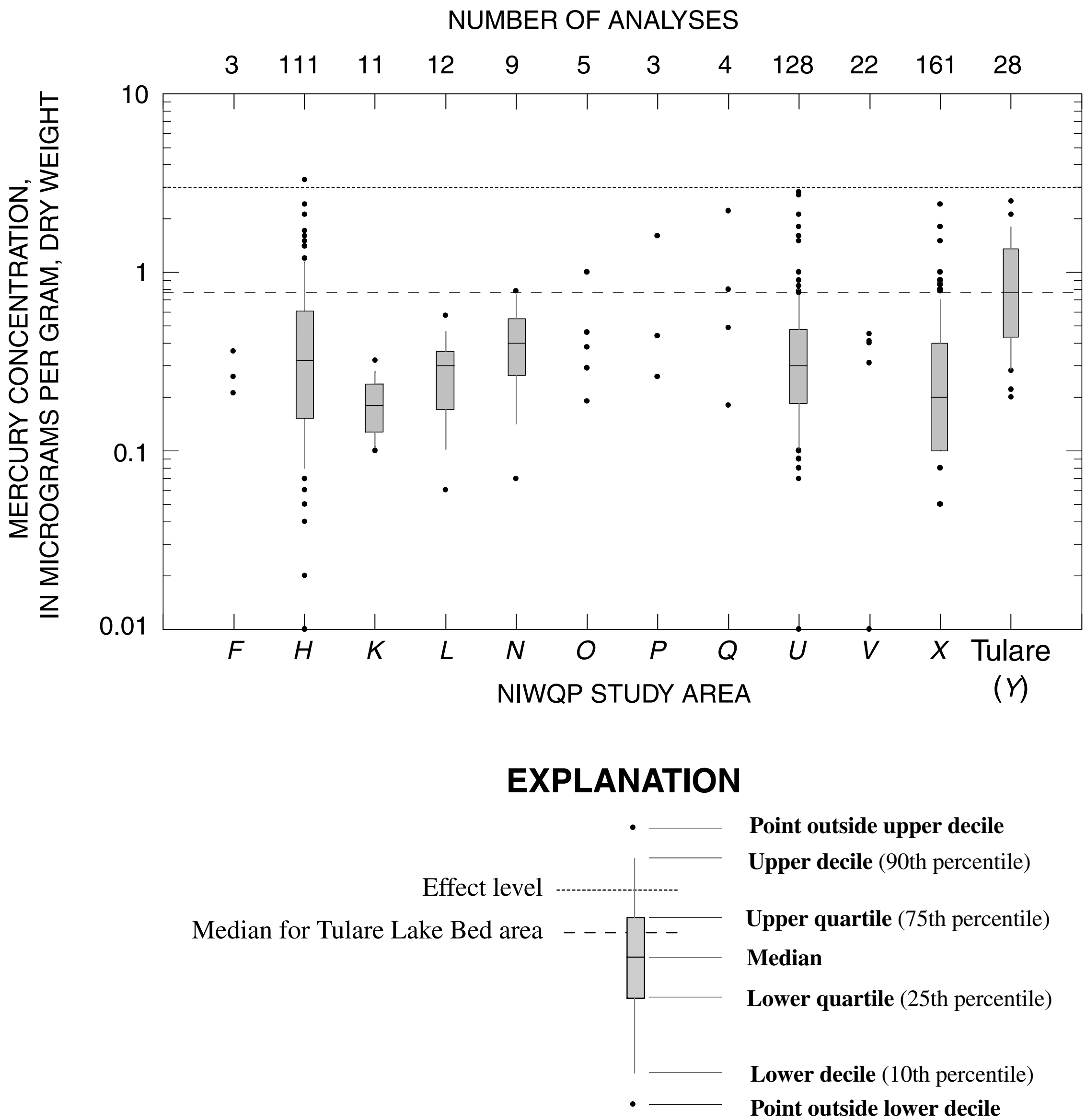


FIGURE 40. Comparison of mercury concentrations in stilt and avocet eggs from National Irrigation Water Quality Program (NIWQP) study areas to concentrations in stilt eggs from the Tulare Lake Bed area in California. Data for Tulare Lake Bed area are from Schroeder and others (1988) and U.S. Fish and Wildlife Service (unpublished data).

In summary, teratogenic-response curves for avian-egg exposure to selenium in the San Joaquin Valley were expected to be free of significant confounding interaction effects and to be applicable to most, if not all, the other NIWQP study areas. Furthermore, examination of the multielement-response data conclusively reinforced focusing on selenium for risk assessment (fig. 38). Thus, not only in theory is selenium alone sufficient to explain the avian teratogenesis associated with irrigation-induced aquatic contamination (Hoffman and Heinz, 1988), selenium appears to be the only teratogenic agent operating in the NIWQP study areas.

TERATOGENIC-RESPONSE CURVES FOR SELENIUM EXPOSURE

One of the principal objectives of the San Joaquin Valley Drainage Program, through contracts with the USFWS Patuxent Wildlife Research Center, was to develop predictive criteria for avian selenosis (U.S. Fish and Wildlife Service, 1990). Therefore, a broad-scale program to collect response data for avian teratogenesis at selenium-effected and reference sites of the San Joaquin Valley was initiated in 1987 (Schroeder and others, 1988; Skorupa and Ohlendorf, 1988, 1989, 1991; Ohlendorf and Skorupa, 1989; Moore and others, 1990; Robinson and others, 1997; Skorupa, 1998). Upon completion of the San Joaquin Valley Drainage Program in 1990, field sampling in the San Joaquin Valley continued under the sponsorship of the USFWS, California Department of Water Resources, BOR, and NIWQP. Sampling continued through the 1997 field season; the largest cumulative sampling effort was in the Tulare Lake Bed area (*Y*) in the lower San Joaquin Valley.

During 1972–85, about 25 shallow impoundments were constructed in the Tulare Lake Bed area to allow for evaporative disposal of water from subsurface irrigation drains. These facilities varied from large (>1,200-acre) multiple-celled systems (similar in design to Kesterson Reservoir) to small (<25-acre) single-celled ponds. The selenium content of water discharged to the different evaporation basins ranged from less than 1 µg/L to greater than 1,000 µg/L. Although the facilities were not intended to provide wildlife benefits, the ponds proved attractive to waterbirds and two species of breeding waterbirds, American avocets and black-necked stilts, were widespread at the evaporation ponds. Avian eggs spanning more than 2 orders of magnitude in selenium content (<1 to >100 µg/g) were available for sampling at the evaporation basins and local reference sites. In effect, a set of field conditions that were nearly ideal for documenting selenium exposure-response relations had been created unintentionally in this area. By 1996, the Tulare multi-element-response data, supplemented with data from Kesterson Reservoir, from the Grasslands Water District in California, and from several NIWQP study areas (Ohlendorf and others, 1986; Stephens and others, 1992; Blanchard and others, 1993; Hothem and Welsh, 1994a,b; U.S. Fish and Wildlife Service, unpublished data), constituted a substantive basis for delineating teratogenic-response functions (table 29).

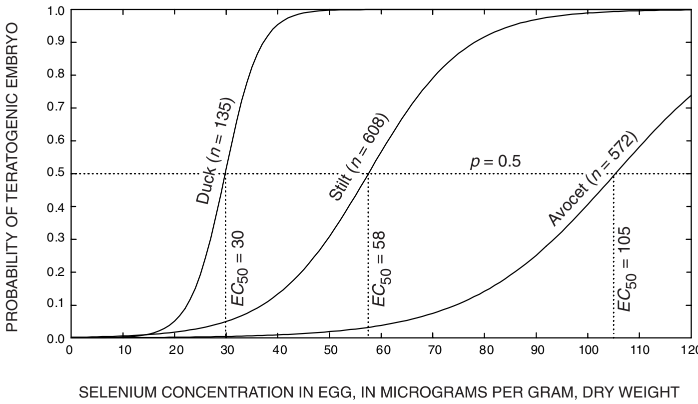
Logistic-regression response functions were developed for ducks, stilts, and avocets (fig. 41). The data for these functions were derived by assessing the condition of an embryo during the processing of the sample for chemical analysis and then matching the chemical results to the individual embryo assessments. Thus, each data point represents the exposure (chemistry) data and response (embryo-assessment) data for the same egg. These individually paired data produced reasonably precise response functions. (Regression-coefficient standard errors ranged from 10 to 30 percent.) The stilt and avocet curves are species specific, whereas the duck curve is a composite derived primarily from data for gadwalls, mallards, pintails, and redheads (including a few data points from ruddy ducks, shovelers, and canvasbacks). The response function for 53 mallard eggs does not differ significantly from the multispecies composite function (EC_{50} = 29 µg/g for mallard data compared to EC_{50} = 30 µg/g for multispecies composite data).

TABLE 29. *Number of avian embryos analyzed for selenium content and assessed for teratogenesis*

[Symbol: —, not applicable or none]

Study area		Embryos		
Identifier[1]	Name or description	Avocet	Stilt	Duck
National Irrigation Water Quality Program study areas:				
F	Gunnison River Basin–Grand Valley Project, Colorado	—	—	7
H	Kendrick Reclamation Project, Wyoming	14	—	—
N	Middle Green River Basin, Utah	—	—	2
P	Milk River Basin, Montana	22	—	—
V	San Juan River area, New Mexico	2	—	—
X	Sun River area, Montana	123	—	1
Other study areas:				
—	Grasslands, water district[2]	4	6	41
—	Honey Lake Valley, California[3]	2	1	—
—	Kesterson Reservoir, California[4]	35	80	31
—	Redrock Ranch near Fresno, California[5]	—	14	—
—	Tulare Lake Bed Area, California[6]	370	507	53
	Total.............................	572	608	135

[1] Used in figure 2 to show locations of National Irrigation Water Quality Program study areas.
[2] From study by Hothem and Welsh (1994a, b).
[3] From study by Robinson (1996).
[4] From study by Ohlendorf and others (1986).
[5] E. Van Vorts, California Regional Water Quality Board, Central Valley Region, written commun., 1996.
[6] From study by Skorupa (1998) and U.S. Department of the Interior (1998).



GENERAL LOGISTIC MODEL

$$p = (e^{(\beta_0+\beta_1 X)}) \div [1+e^{(\beta_0+\beta_1 X)}]$$

	Model coefficients		
	Duck	Stilt	Avocet
β_0	-8.973	-6.136	-7.479
β_0 Standard error:	2.341	0.578	1.179
β_1	0.2978	0.1067	0.0710
β_1 Standard error:	0.0881	0.0116	0.0144

PREDICTIONS BASED ON MODEL

	Selenium effect concentrations (micrograms per gram, dry weight)		
	Duck	Stilt	Avocet
EC_{01}	15	14	41
EC_{10}	23	37	74
EC_{50}	30	58	105

FIGURE 41. Teratogenic-response functions for ducks, stilts, and avocets. Based on 1983–96 field data. EC_x, predicted concentration at which x percent of embryos will be teratogenic; *n*, number of samples.

Each function in figure 41 was generated by first calculating a base function for each taxon from the Tulare data. To test within each taxon for significant differences among the data sets summarized in table 29, the Tulare functions then were used to generate expected frequencies of teratogenesis for all other data sets. None of the observed frequencies of teratogenesis in those other data sets were significantly different from the expected frequencies. Therefore, all sets of data within each taxon (ducks, stilts, avocets) were pooled to generate the final response functions (fig. 41). Sufficient Kesterson and Tulare stilts data were available to allow comparison of the actual site-specific response curves, and they were found to be statistically indistinguishable (fig. 42). In summary, in the available data no evidence was discernible for site-specific teratogenic response. All logistic-regression analyses were completed by using the nonlinear-estimation module of the Statistica software package (StatSoft, 1995).

On the basis of the selenium-response coefficients (β_0 and β_1 in fig. 41) and their standard errors, all three teratogenic-response functions in figure 41 are statistically distinct (p <0.03 for Z-tests of all coefficients (Afifi and Clark, 1996)). On the basis of EC_{50} estimates, stilts are about twice as sensitive as avocets to embryonic selenium exposure, and ducks are about four times as sensitive as avocets. These response curves cover about a fourfold range of interspecies sensitivity. Until more species are studied, the duck, stilt, and avocet curves serve as best estimates for generic sensitive-, average-, and tolerant-response functions, respectively.

The duck response curve is steep but is nonetheless consistent with experimental data for game-farm mallards. For instance, when duckling exposure to dietary selenium (as selenomethionine) was doubled from 40 µg/g to 80 µg/g, mortality increased from 12.5 percent to 100 percent (Heinz and others, 1988). Teratogenic-response functions shown in figure 41 indicate that doubling of duck eggs' exposure to selenium from about 20 µg/g to about 40 µg/g causes the incidence of teratogenesis to increase from about 5 percent to about 95 percent in the duck embryos. Although the life stages and endpoints differ in this comparison, they both show a similarly steep exposure-response function for selenium. This close correspondence between experimental and field data for ducks again suggests a general absence of meaningful interaction effects in the field samples. Selenium alone appears sufficient to explain the shapes of the curves generated from field data.

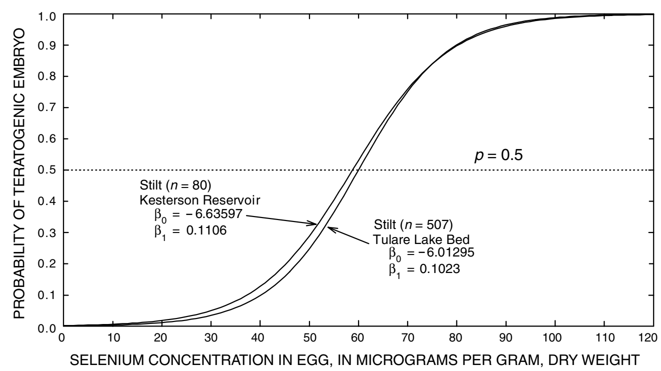


FIGURE 42. Teratogenic-response functions for stilts at Kesterson Reservoir during 1983–85 and in Tulare Lake Bed area during 1987–95. β_0 and β_1, selenium-response coefficients; *n*, number of samples.

NATIONAL IRRIGATION WATER QUALITY PROGRAM TERATOGENIC-RISK ASSESSMENT

The three teratogenic-response functions presented in figure 41 provide a rigorous basis for quantitative risk assessment. The true multispecies risk for freshwater aquatic birds is probably bounded by the extreme estimates (ducks and avocets) and perhaps is estimated best by using a stilt (or average sensitivity) standard for overall risk assessment. By applying all three response equations to the concentrations of selenium in eggs as documented for each NIWQP study area, a range of teratogenic-risk estimates can be generated ranging from sensitive (paralleling the duck standard) to tolerant (paralleling the avocet standard).

On the basis of logistic-regression probabilities, the predicted rates of embryo teratogenesis for each NIWQP study area were calculated and are presented in table 30. The predicted values were obtained by summing the probabilities and dividing by sample size. The results for the 23 NIWQP study areas where avian eggs were collected, when compared to avian sensitivity standards, suggest that avian exposure to selenium was elevated sufficiently to cause teratogenic effects at 6 study areas (26 percent) on the basis of the duck standard (sensitive), 5 (22 percent) on the basis of the stilt standard (average), or 2 (9 percent) on the basis of the avocet standard (tolerant). In summary, about 75 percent or more of the NIWQP study areas are predicted to have insufficient avian exposure to selenium to induce embryo teratogenesis.

Under the worst-case risk scenario for teratogenesis (duck standard), the median predicted magnitude of impact at effect sites is 9.7 percent. It is unlikely that a median 10-percent teratogenic effect would be demographically tolerable for many populations of breeding ducks in the long term. Greenwood and others (1995) estimates that 15- to 20-percent nest success is the demographic break-even point for demographic sufficiency for most species of ducks. However, largely due to the poor quality of extant nesting habitat, rates of nest predation commonly are high and nest success often is near the break-even point. For example, a 4-year study (1982–85) of ducks nesting throughout the Canadian prairie pothole region found that the best overall nest success rate was only 17 percent

TABLE 30. *Predicted rates of avian teratogenesis in National Irrigation Water Quality Program study areas*

[Abbreviation and symbol: B, background; µg/g, micrograms per gram; —, no avian eggs collected from study area]

Study area		Predicted rate of teratogenesis based on avian sensitivity standards[1] (percent)		
Identifier[2]	Name	Duck standard (sensitive: EC_{50} = 30 µg/g)	Stilt standard (average: EC_{50} = 58 µg/g)	Avocet standard (tolerant: EC_{50} = 105 µg/g)
A	American Falls Reservoir, Idaho	B	B	B
B	Angostura Reclamation Unit, South Dakota	B	B	B
C	Belle Fourche Reclamation Project, South Dakota	B	B	B
D	Columbia River Basin, Washington	B	B	B
E	Dolores–Ute Mountain area, Colorado	B	B	B
F	Gunnison River Basin–Grand Valley Project, Colorado	7.7	1.9	B
G	Humboldt River area, Nevada	B	B	B
H	Kendrick Reclamation Project, Wyoming	68.6	56.6	13.4
I	Klamath Basin Refuge Complex, California–Oregon	B	B	B
J	Lower Colorado River valley, California–Arizona	—	—	—
K	Lower Rio Grande valley, Texas	—	—	—
L	Malheur National Wildlife Refuge, Oregon	B	B	B
M	Middle Arkansas River Basin, Colorado–Kansas	B	B	B
N	Middle Green River Basin, Utah	11.6	4.9	.7
O	Middle Rio Grande, New Mexico	B	B	B
P	Milk River Basin, Montana	B	B	B
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	B	B	B
R	Pine River area, Colorado	B	B	B
S	Riverton Reclamation Project, Wyoming	B	B	B
T	Sacramento Refuge Complex, California	B	B	B
U	Salton Sea area, California	0.7	B	B
V	San Juan River area, New Mexico	B	B	B
W	Stillwater Wildlife Management Area, Nevada	B	B	B
X	Sun River area, Montana	1.4	.7	B
Y	Tulare Lake Bed area, California	27.9	4.4	B
Z	Vermejo Project area, New Mexico	—	—	—
	Median for all areas	B	B	B
	Median for "effect areas"[3]	9.7	3.2	B

[1] Rate calculated by applying logistic-response equations to concentrations of selenium in avian eggs reported for each study area. Avian standards based on logistic-response equations for ducks, black-necked stilts, and american avocets (fig. 43). Background: fewer than 5 deformed embryos per 1,000 examined, or <0.5 percent.

[2] Used in figure 2 to show locations of study areas.

[3] Areas where rate of teratogenesis is above background.

(Greenwood and others, 1995). A more localized study of ducks nesting in the grasslands in central California (Hothem and Welsh, 1994b) also found that nest success was commonly less than 20 percent due to high rates of nest predation. Under such circumstances, a 10-percent teratogenic effect, even if highly duplicative of predation losses, could push local populations from being demographic sources to being demographic sinks. This is especially true considering that a 10-percent teratogenic effect would be supplemented by nonteratogenic embryo inviability (Stanley and others, 1996) and losses after hatching (Heinz and others, 1989; Ohlendorf, 1989; Williams and others, 1989), which in turn would affect demographic sufficiency. However, considering the teratogenic-risk factors for all 23 assessable NIWQP study areas, the median predicted magnitude of teratogenic effect for ducks is 0 percent (table 30). Therefore, throughout the Western United States, the overall teratogenic effect of irrigation-induced aquatic contamination seems unlikely to threaten the net demographic status of even sensitive species, although local teratogenic effects might be important at some irrigation-influenced aquatic habitats.

The above conclusions depend on the reliability of the teratogenesis predictions (table 30). One independent way to assess that reliability is to use the predictions as input data for power analyses and then compare the power-analysis results to actual observations. The power of a study to detect one or more deformed avian embryos is a function of the true rate of terata and the number of assessable embryos that are randomly sampled. Based on laws of binomial probability, this relation can be quantified by the following equation:

$$P_d = 1 - (1 - T)^n \qquad (6)$$

where P_d is power (for detecting one or more deformed embryos),
T is probability of teratogenesis, and
n is number of embryos examined.

For example, the probability of teratogenesis in the Salton Sea area (*U*) was predicted to be 0.7 percent ($T = 0.007$) using a duck standard of sensitivity and the selenium content of the eggs collected in that study area. A total of 65 embryos were examined during the NIWQP study. Thus, the predicted power of the study to detect one or more deformed avian embryos was $P_d = 1-(1-0.007)^{65} = 0.367$ (37 percent). Because 37 percent is less than a 50-percent chance of finding a deformed embryo, the prediction is that no deformities would be found. In fact, no deformities were found among the species whose eggs were sampled during the study. For this test case, because the predicted rate of teratogenesis ($T = 0.007$) yielded a power-analysis prediction that matches field observations, the predicted rate of teratogenesis seems to be reliable. Similar power-analysis results and associated predictions for all assessable NIWQP study areas and for all three embryo-sensitivity standards are shown in table 31 .

For 13 of the 14 study areas that reported embryo-assessment data, the power-analysis predictions regarding ability to detect deformities matched the observed outcomes of the studies. Only the Sun River area (*X*) showed a disagreement between predicted and observed outcomes (table 31). That study area was unusual because most of the embryos assessed for teratogenesis did not come from eggs submitted for chemical analysis (Nimick and others, 1996). Out of 759 assessed eggs, 579 duck eggs were examined for embryo status without being submitted for chemical analysis. Therefore, relative to the sample of assessed embryos, duck eggs were underrepresented in the sampling of egg chemistry. Only 58 percent of the bird eggs analyzed for selenium were duck eggs while 76 percent of eggs assessed for embryo condition were duck eggs. This is a potentially important bias because grebe and avocet eggs, the other primary components of the egg-chemistry data set, on average contained about twice as much selenium as the duck eggs (11 µg/g compared to 5.5 µg/g). Thus, the predicted probability of finding one or more selenium-induced teratogenic embryos was based on a set of eggs having substantially greater selenium exposure than the set of eggs used for embryo assessment. As a result, the calculated probability of finding selenium-induced teratogenesis was overestimated for the area. This might explain why the predicted outcome for detection of selenium-induced terata was “yes” whereas the observed outcome was “no” (table 31).

Power-analysis predictions were correct for 13 of the 14 study areas which strongly supports the reliability of the teratogenic-risk assessments throughout the Western United States. According to binomial probability, the likelihood of such a high incidence of matches between predictions and observations by pure chance is < 0.001. The high level of predictive accuracy is probably due, at least in part, to the lack of toxicologically significant arsenic or mercury exposures in the NIWQP study areas (see section titled “Relevance of Arsenic and Mercury,” p. 94).

NATIONAL IRRIGATION WATER QUALITY PROGRAM EMBRYO-VIABILITY ASSESSMENT

Embryo teratogenesis is a relatively insensitive response variable for avian selenosis. Comparatively subtle physiological effects causing embryo inviability (eggs that are unable to hatch) can occur at exposures to selenium in the egg that are less than the levels required for overt structural deformities. For example, three recent selenium-dosing experiments on captive game-farm mallards found that when hens produced sets of eggs averaging 6.8, 13.1, 57.5, and 67.9 percent teratogenic embryos, the corresponding rates of embryo inviability were 38.5, 53.0, 90.7, and 96.3 percent (Heinz and others, 1987, 1989; Stanley and others, 1994). In these studies, rates of teratogenesis consistently underestimated the rates of total selenium-induced embryo mortality by about 30 to 40 percent. This outcome most recently was reaffirmed by Stanley and others (1996), when they found a 34-percent rate of embryo inviability associated with selenium exposure in the egg to be just below the threshold for teratogenesis.

TABLE 31. *Power analysis of avian data for detecting selenium-induced terata in National Irrigation Water Quality Program study areas*

[Upper boundary of background rates of teratogenesis conservatively estimated to be 0.5 percent. Symbols: —, not applicable; <, less than; >, greater than]

Study area		Number of embryos assessed[2]	Power to detect one or more deformities[3]			Detection of selenium-induced terata	
Identifier[1]	Name		Duck standard	Stilt standard	Avocet standard	Predicted[4]	Observed
A	American Falls Reservoir, Idaho	0	—	—	—	—	—
B	Angostura Reclamation Unit, South Dakota	0	—	—	—	—	—
C	Belle Fourche Reclamation Project, South Dakota	0	—	—	—	—	—
D	Columbia River Basin, Washington	<58	<0.25	<0.25	<0.25	No	No
E	Dolores–Ute Mountain area, Colorado	<15	<.07	<.07	<.07	No	No
F	Gunnison River Basin–Grand Valley Project, Colorado	>65	>.99	>.71	>.28	Yes	Yes
G	Humboldt River area, Nevada	<37	<.17	<.17	<.17	No	No
H	Kendrick Reclamation Project, Wyoming	137	1.00	1.00	1.00	Yes	Yes
I	Klamath Basin Refuge Complex, California–Oregon	0	—	—	—	—	—
J	Lower Colorado River valley, California–Arizona	0	—	—	—	—	—
K	Lower Rio Grande valley, Texas	0	—	—	—	—	—
L	Malheur National Wildlife Refuge, Oregon	<47	<.21	<.21	<.21	No	No
M	Middle Arkansas River Basin, Colorado–Kansas	0	—	—	—	—	—
N	Middle Green River Basin, Utah	173	1.00	1.00	1.00	Yes	Yes
O	Middle Rio Grande, New Mexico	0	—	—	—	—	—
P	Milk River Basin, Montana	0	—	—	—	—	—
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	0	—	—	—	—	—
R	Pine River area, Colorado	<23	<.11	<.11	<.11	No	No
S	Riverton Reclamation Project, Wyoming	0	—	—	—	—	—
T	Sacramento Refuge Complex, California	18	.09	.09	.09	No	No
U	Salton Sea area, California	65	.37	.28	.28	No	No[5]
V	San Juan River area, New Mexico	7	.03	.03	.03	No	No
W	Stillwater Wildlife Management Area, Nevada	109	.42	.42	.42	No	No
X	Sun River area, Montana	759	1.00	1.00	.98	Yes	No[6]
Y	Tulare Lake Bed area, California	93	1.00	.98	.37	Yes	Yes
Z	Vermejo Project area, New Mexico	0	—	—	—	—	—

[1] Used in figure 2 to show locations of study areas.

[2] For some study areas, reports describing investigations did not specify number of embryos assessed. This uncertainty is reflected herein by use of symbols "<," or ">" preceding number of assessed embryos. See text for discussion. Sample sizes in this table may also differ from those listed for 'Birds' in table 9 because that table includes samples of all types of bird tissue and excludes eggs that were examined but not chemically analyzed.

[3] Power determined by predicted rates of teratogenesis (see table 27) and by number of embryos assessed for deformities.

[4] Detection of one or more deformities is predicted "Yes" if power calculation for stilt standard is greater than 0.5.

[5] Deformities were detected, but types detected (twinning; crossed bills) typically are induced by organochlorines, which are highly elevated in this area (Setmire and others, 1993).

[6] Deformed embryos were found but did not come from eggs having elevated selenium concentrations and are most reasonably interpreted as representing normal background teratogenesis. The large sample of assessed embryos made it highly likely that one or more deformed embryos would be detected even if teratogenesis were occurring at background rates (less than about 0.5 percent).

Owing to the low sensitivity of teratogenesis as a response variable, many of the NIWQP study areas that were classified as sites having no teratogenic effects (table 30) may still be at risk for depression of egg hatchability as severe as 30 to 40 percent. In field studies, relating egg viability directly to selenium concentrations in the egg is difficult because the viability of an egg is determined ultimately by whether it hatches when incubated to full term in the field. By the time a clutch of eggs hatches, however, only the failed-to-hatch eggs remain to be sampled for chemical analysis, and failed-to-hatch eggs would be a biased subset of all eggs. An indirect alternative approach is to use the sample-egg technique (Blus, 1982; Ohlendorf, 1993), whereby a sample egg is randomly selected from a clutch for chemical analysis and the chemical content of sampled eggs is related to the hatchability (viability) of the uncollected sibling eggs (whose fate must be monitored by repeated followup visits to the nest).

The inviability-response functions so generated are at the level of the hen, rather than at the level of the individual egg. To successfully characterize an inviability-response function while using the sample-egg technique, contaminant exposure among the eggs within an individual clutch must be reasonably uniform; that is, the selenium content of the sample egg must reasonably represent the sibling eggs. At adequate sample sizes ($n > 100$), gross violation of the within-clutch uniformity assumption is unlikely to produce a statistically significant response where none exists but would be expected to reduce the chances of statistically discerning, biologically authentic responses. Therefore, whenever a strong response function was produced by the sample-egg method, the selenium contents of sibling eggs likely were similar.

An important statistical constraint that applies to inviability-response functions is that sibling eggs are not independent samples. When dealing with sibling eggs, hens are the independent units being sampled. Thus, hen effect, rather than embryo effect, is the applicable response variable for studies using the sample-egg technique. By comparison, teratogenesis assessments can focus at the level of the embryo because teratogenic-response curves are generated from samples of unrelated (non-sibling) eggs. Categorical presence or absence of hen effect (a binomial-response variable analogous to presence or absence of terata in sample embryos) can be assessed by determining whether one or more inviable sibling eggs are present in a sample clutch. Unlike background rates of embryo teratogenesis that are close to 0 (0.5 percent), background rates of avian clutches containing one or more inviable eggs are considerably greater than 0 (almost 9 percent) due to the normal incidence of infertile eggs and other normal reproductive dysfunctions. Thus, the interpretation of inviability-response functions must account for a response baseline greater than 0. The raw probabilities of hen effect must be adjusted for such a nonzero baseline in order to assess contaminant-induced responses appropriately.

As part of the studies funded by the San Joaquin Valley Drainage Program, the incidence of inviable embryos from individual clutches and therefore from individual hens was recorded for about 300 full-term nests of black-necked stilts from which a random sample egg also had been removed and analyzed for selenium content. To calculate a hen-specific inviability-response function, 409 data points were compiled from studies at Kesterson National Wildlife Refuge (U.S. Fish and Wildlife Service, unpublished data) and a study in the Salton Sea area (*U;* U.S. Fish and Wildlife Service, unpublished data). An inviability-response curve was produced by logistic regression (Afifi and Clark, 1996):

$$p = e^{(-2.327 + 0.0503\,X)} \div [1 + e^{(-2.327 + 0.0503\,X)}]\,, \qquad (7)$$

where p is probability of one or more inviable eggs in sampled clutch; and

X is selenium content of random-sample egg, in micrograms per gram, dry weight.

At $X = 0$, equation 7 yields an estimate of 8.9 percent for the background rate of clutches containing one or more inviable eggs (mostly due to naturally occurring infertility). On the basis of an analysis of the clutch-specific inviability data for stilts presented by Skorupa (1998), this background rate would be expected to apply for selenium exposures of as much as 6 μg/g in the egg. For exposures greater than 6 μg/g, equation 7 would be expected to apply. These two conditions were applied to the NIWQP data base to calculate the predicted incidence of reproductively impaired hens at each study site. Those raw incidences were converted to estimates of selenium-induced rates of hen effect by correcting for the 8.9-percent normal background rate of effected hens. Calculation of the predicted incidence (selenium-effected hens) was done by using the following equation:

$$H_a = [(1\text{-}H_{bk}) - (1\text{-}H_{raw})] \div (1\text{-}H_{bk})\,, \qquad (8)$$

where H_a is proportion selenium-effected hens;

H_{raw} is predicted incidence of effected hens calculated using equation 7; and

H_{bk} is normal background rate of effected hens.

The predicted incidence (H_{raw}) of effected hens is based on selenium exposure and is calculated by using equation 7. Thus, if $H_{raw} = 0.10$ and $H_{bk} = 0.089$, then the estimate of selenium-effected hens would be

$$H_a = [(1\text{-}.089) - (1\text{-}.10)/(1\text{-}.089)] = [(0.911\text{-}0.900) / (0.911)] = 0.012\,.$$

Normally 91.1 percent of all hens whose nests went to full term would hatch all their eggs. At the hypothetical study site, the selenium content of the eggs was high enough to predict that only 90 percent of full-term nests would hatch all their eggs. That reduction of 1.2 percent compared to normal was used to estimate the level of selenium-induced hen effects. This can be expressed in demographic terms as 12 effected hens per 1,000 breeding hens exposed at the study site.

As an example calculation, the selenium concentrations of the 10 bird eggs collected from the Belle Fourche Reclamation Project (table 32) were used to estimate how many breeding hens would lose eggs to selenium poisoning in that area. For instance, the probability of the blue-winged teal hen's clutch (table 32) having one or more inviable eggs (based on the stilt standard) was estimated from equation 7:

$$p = e^{[-2.327 + (0.0503 \times 8.0)]} \div \{1 + e^{[-2.327 + (0.0503 \times 8.0)]}\} = 0.127.$$

The mean probability for all the eggs from the study area is 0.107, or 10.7 percent (table 32). This probability includes the normal background rate of egg inviability (0.089, or 8.9 percent) and must be corrected to determine the excess inviability caused by selenium toxicity. This is done by using equation 8 to calculate selenium-effected hens:

$$H_a = [(1 - 0.089) - (1 - 0.107)] / (1 - 0.089) = 0.0198 .$$

Thus, the average probability of a Belle Fourche Reclamation Project (*C*) hen's having an inviable egg as a result of selenium poisoning is about 2 percent.

TABLE 32. *Calculation of probability of hen effect, Belle Fourche Reclamation Project (C), South Dakota*

Species	Selenium in single egg (micrograms per gram)	Probability of hen effects[1]
Red-winged blackbird	2.2	0.089
	1.9	.089
	1.8	.089
	3.8	.089
Pied-billed grebe:	9.6	.136
	10	.139
	9.0	.133
Mallard	.1	.089
Northern pintail	1.3	.089
Blue-winged teal	8.0	.127
Mean....................................		.107

[1] A background rate of 0.089 was used for selenium concentrations ≤6 micrograms per gram. For selenium concentrations >6 micrograms per gram, probability was calculated using equation 7.

Characteristics of the NIWQP data base relevant to assessing the risk of avian embryotoxicity (egg inviability), including projected rates of selenium-induced hen effects, are presented in table 33. Of the 23 NIWQP study areas where avian eggs were sampled, 14 (61 percent) were projected to have at least some degree of selenium-induced depression of egg viability on the basis of eggs containing selenium concentrations that exceeded the stilt threshold for embryotoxic risk, 6 µg/g selenium (Skorupa, 1998). Of the 2,055 avian eggs sampled for the NIWQP, 906 (44 percent) contained more than 6 µg/g of selenium. The median rates of exceedance were 7.7 percent for the 23 study areas sampled and 40.1 percent for the 14 study areas that had one or more eggs exceeding the threshold.

The median projected rate of selenium-effected hens was only 0.9 percent for the 23 study areas where bird eggs were collected. For the 14 study areas where eggs containing more than 6 µg/g were found, the median projected rate of selenium-effected hens was 2.2 percent. The actual rates in the study areas may be higher because in many of the projected no-effect study areas few eggs were sampled (table 33). For example, the Humboldt River area (*G*) is listed as a no-effect area, but avian eggs were sampled at only one site within the study area. However, subsequent sampling within that area showed that avian eggs having selenium concentrations exceeding 6 µg/g do occur there (Seiler and Tuttle, 1997).

Across the 23 study areas sampled for avian eggs by the NIWQP, eggs were collected from 161 individual sampling sites (table 33). One or more eggs exceeding the stilt threshold for egg inviability were collected at 79 (49 percent) of the 161 sites. At those 79 effect sites, the median projected rate of selenium-effected hens was 3.9 percent (39 per 1,000 exposed; interquartile range, 1.3 to 6.5; fig. 43). An alternative method

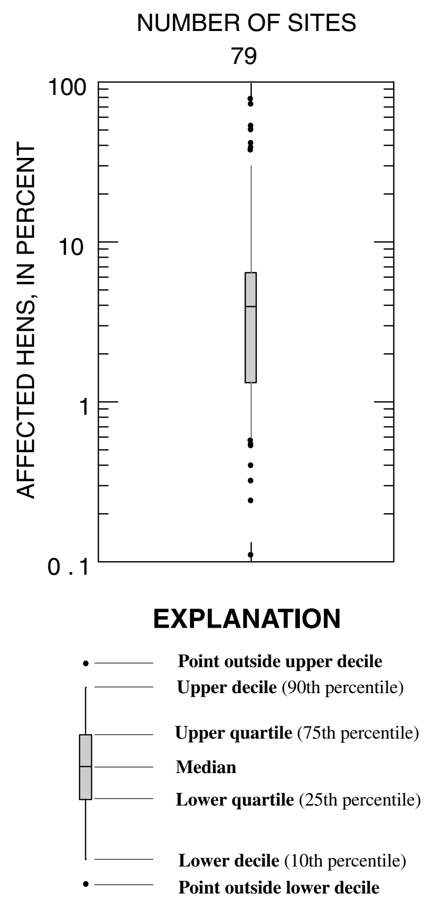


FIGURE 43. Statistical summary of projected magnitude of selenium-induced hen effects at sites with one or more eggs exceeding stilt standard (intermediate sensitivity) for embryotoxicity.

TABLE 33. *Summary of predicted avian embryotoxicity in National Irrigation Water Quality Program study areas*

[Abbreviation and symbol: µg/g, micrograms per gram; —, not applicable]

Study area		Number of sites sampled	Number of sites where at least one sampled egg had greater than 6 µg/g selenium	Total number of eggs sampled	Number of eggs having greater than 6 µg/g selenium[2]	Exceedance (percent)	Predicted percent effected hens[3]	Area ranking[4]
Identifier[1]	Name							
A	American Falls Reservoir, Idaho	5	0	13	0	0	0	19
B	Angostura Reclamation Unit, South Dakota	2	0	8	0	0	0	19
C	Belle Fourche Reclamation Project, South Dakota	5	2	10	4	40.0	2.0	8
D	Columbia River Basin, Washington	6	0	29	0	0	0	19
E	Dolores–Ute Mountain area, Colorado	4	1	15	2	3.3	1.1	11
F	Gunnison River Basin–Grand Valley Project, Colorado	16	14	91	77	84.6	8.5	4
G	Humboldt River area, Nevada	1	0	37	0	0	0	19
H	Kendrick Reclamation Project, Wyoming	8	7	400	359	89.8	55.6	1
I	Klamath Basin Refuge Complex, California–Oregon	2	0	31	0	0	0	19
J	Lower Colorado River valley, California–Arizona	0	—	—	—	—	—	—
K	Lower Rio Grande valley, Texas	0	—	—	—	—	—	—
L	Malheur National Wildlife Refuge, Oregon	3	0	47	0	0	0	19
M	Middle Arkansas River Basin, Colorado–Kansas	2	2	9	6	66.6	2.6	6
N	Middle Green River Basin, Utah	37	23	399	193	48.4	8.6	3
O	Middle Rio Grande, New Mexico	3	0	15	0	0	0	19
P	Milk River Basin, Montana	3	0	9	0	0	0	19
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	4	0	19	0	0	0	19
R	Pine River area, Colorado	3	1	23	5	21.7	1.2	10
S	Riverton Reclamation Project, Wyoming	5	2	15	7	46.7	2.9	5
T	Sacramento Refuge Complex, California	6	1	20	1	5.0	.2	14
U	Salton Sea area, California	9	6	128	15	11.7	.7	13
V	San Juan River area, New Mexico	9	1	13	1	7.7	.9	12
W	Stillwater Wildlife Management Area, Nevada	7	4	92	37	40.2	1.9	9
X	Sun River area, Montana	20	14	620	188	30.3	2.3	7
Y	Tulare Lake Bed area, California	1	1	12	11	91.7	16.2	2
Z	Vermejo Project area, New Mexico	0	—	—	—	—	—	—
	Totals	161	79	2,055	906	—	—	—
	Median for 23 study areas where eggs were collected					7.7	0.9	
	Median for 14 study areas where exceedance >0					40.1	2.2	

[1] Used in figure 2 to show locations of study areas.

[2] On basis of stilt standard of sensitivity, eggs having selenium concentration greater than 6 micrograms per gram, dry weight, exceed embryotoxicity threshold (Skorupa, 1998). Because stilts show average sensitivity to selenium poisoning (see table 30), stilt standard was chosen for general assessment of toxic effects.

[3] Based on specific locations and species sampled in study area, percentage of nesting hens that would lay at least one selenium-poisoned egg.

[4] Ranking of 23 study areas where bird eggs were collected from most to least contaminated on the basis of the percent of hens effected by selenium.

for projecting the overall rate of hen effects, which is less susceptible to the zero bias caused by low sampling intensity in some study areas, would be to multiply the median projection for hen effects at effect sites (3.9 percent) by the proportion of effect sites in the data base (0.49). This calculation suggests that a more accurate projection of the overall rate of hen effects in NIWQP study areas would be 19 per 1,000. Thus, across all 23 sampled study areas, 1.9 percent of hens would be expected to have one or more of their eggs made inviable because of elevated selenium content.

The projected rate of overall hen effects, 1.9 percent, is substantially lower than the overall exceedance rate for embryotoxic risk, 7.7 percent, because most exceedances occur within the region of the inviability-response curve (eq. 6), where the probability is low that exceedance would cause toxicity. Of the 79 effect sites yielding avian eggs sufficiently contaminated with selenium to project effects, only 8 would be expected to have an effects rate of a magnitude at least as large as at Kesterson National Wildlife Refuge (fig. 44). However, the most common finding at effect sites was a modest-magnitude effects rate (less than or equal to 10 percent selenium-effected hens, compared to greater than 30 percent at Kesterson Reservoir).

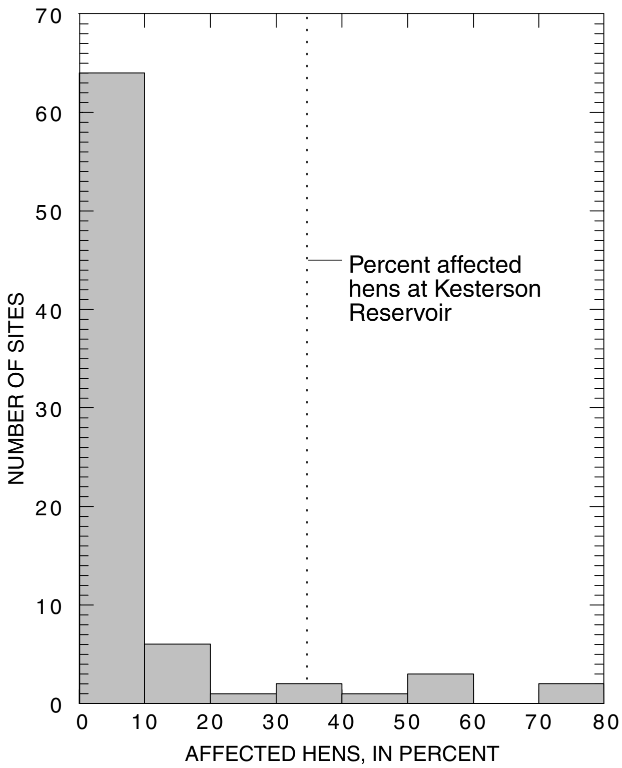


FIGURE 44. Magnitude of predicted hen effects at 79 National Irrigation Water Quality Program data-collection sites where selenium concentrations in eggs are sufficient to reduce hatchability.

DEMOGRAPHIC CONTEXT OF PROJECTED AVIAN EFFECTS

The ultimate biological question for the NIWQP is whether irrigation-induced contamination of aquatic habitats is causing significant biotic effects at the population level. On the basis of avian data, whereby the magnitude of selenium-induced hen effects is projected to exceed 50 percent in some areas, such as in the Kendrick Reclamation Project (*H*), significant avian effects do occur at the population (or subpopulation) level at selected localities. However, on a regional scale, the projected median rates of hen effects are low enough that they must be evaluated more carefully with regard to demographic context before a reasonable interpretation can be made.

The 23 NIWQP study areas were not selected at random; the selection criteria were intended to identify a set of study areas especially prone to irrigation-induced contaminant effects. Therefore, the magnitude of the regional effects rate projected in the Western United States from the NIWQP data base almost certainly represents a worst-case boundary more than a broadly applicable central tendency. Ideally, an estimate of the regional effects rate also should be weighted by the relative importance of different sampling sites to avian populations as reflected by variation in the density of breeding birds attracted to different sampling sites. In the absence of such information, unweighted estimates of effect (table 33; figs. 43 and 44) must be used. That is equivalent to assuming complete independence of spatial variability of contamination from spatial variability of avian distributions across the aquatic habitats of the NIWQP study areas. Because birds are not aware of the contaminants of primary concern when choosing habitat, and in the absence of overt contaminant effects on the structure or makeup of the habitat, such an untested assumption nonetheless may be reasonable.

Another complication is that a binomial hen-specific measure of reproduction (hens effected or not) cannot be evaluated directly for demographic significance. Knowing the percentage of hens producing one or more inviable eggs is not the same as knowing the percentage of eggs that are expected to be inviable. Only the latter expectation can be placed directly into demographic context. However, this complication can be overcome by using nest-monitoring records for stilts nesting in the Tulare Lake Bed area (U.S. Fish and Wildlife Service, unpublished data). The data show a strong relation ($r^2 = 0.83$) between the number of effected eggs and the number of effected hens (table 34; fig. 45); such a relation for stilts expressed as the ratio of percentage effected eggs to percentage effected hens should range from slightly greater than 0.25 to 1.0 in a diminishing incremental-effects (or semilogarithmic) pattern as a function of exposure (as a function of hen effects). Under normal background conditions, only a few of the stilt hens producing inviable eggs (due to natural infertility) would be expected to lay morethan one inviable egg. (Most effected

TABLE 34. *Effected hens and effected eggs of black-necked stilts, Tulare Lake Bed area, California*

[All data collected in 1988–89 from Westfarmers evaporation-pond system (U.S. Fish and Wildlife Service, unpublished data)]

Nesting-neighborhood site-identification number[1,2]	Number of full-term nests[2]	Effected hens[3] (percent)	Number of assessed eggs[2,4]	Effected eggs[5] (percent)
WF01-88	27	7.4	114	2.6
WF06-89	36	11.1	149	6.0
WF11-89	32	12.5	140	7.1
WF05-88	22	13.6	101	7.9
WF10-89	42	19.0	182	9.9
WF03-88	18	22.2	85	12.9
WF07-88	30	40.0	144	27.8
WF08-88	33	54.5	176	44.9

[1] Corporate owner's site-identification number.

[2] Only nesting neighborhoods having more than 15 full-term nests and more than 75 assessed eggs were used in analysis.

[3] Hens clutch contains at least one inviable egg.

[4] Includes eggs from full-term nests and eggs from truncated-term nests whose embryo viability was determined prior to nest predation, flooding, or other cause of nest failure.

[5] Inviable.

hens under background conditions would have one inviable egg per clutch of four, or an expected baseline ratio near 0.25 for percentage effected eggs to percentage effected hens.) However, under conditions of high exposure to selenium, almost 100 percent of the hens would be affected and 100 percent of the eggs would be inviable (thus a ratio of about 1.0 for percentage effected eggs to percentage effected hens). These expectations are matched reasonably well by the field data (fig. 45). A large, multispecies set of data from Kesterson Reservoir yielded rate estimates of 26 percent egg effects and 39 percent hen effects (Ohlendorf, 1989) for a ratio of percentages of 0.67. Even though the relation shown in figure 45 was based solely on data for stilts, the multispecies ratio for Kesterson appears to agree well with it (see *K* in fig. 45). This provides at least some degree of independent validation for the relation and for the assumption that data for a species of intermediate sensitivity, such as the stilt, is indeed appropriate for estimating the central-tendency response of avian-multispecies aggregations.

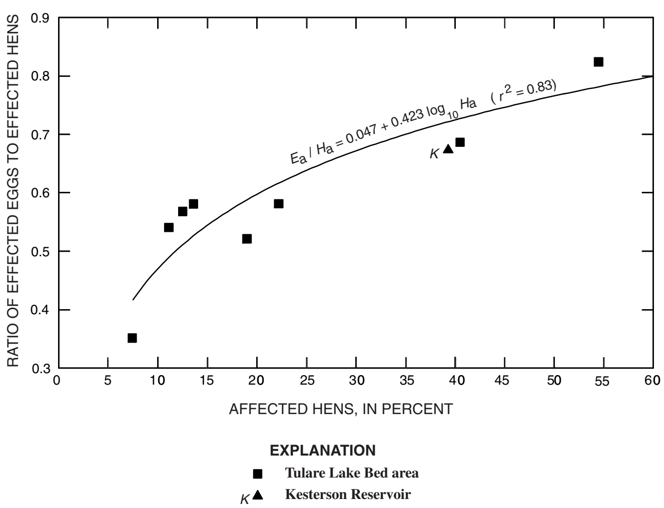


FIGURE 45. Relation between effected eggs (E_a) and effected hens (H_a) for black-necked stilts during 1983–85 at Kesterson Reservoir and during 1988–89 in Tulare Lake Bed area in California.

Using the regression in figure 45, the projection of an overall 1.9-percent hen-effects rate approximately corresponds to 0.3-percent selenium-induced egg inviability. At effect sites, a 3.9-percent hen-effects rate approximately corresponds to 1.2-percent selenium-induced egg inviability. To place these projections fully in demographic context, the inevitable after-hatch toxicity that would be associated with selenium-contaminated environments also must be taken into account. In a controlled experiment using game-farm mallards, the estimated ratio of after-hatch effects to embryonic effects was 1:1, meaning that about 50 percent of all reproductive impairment occurred after hatching (Heinz and others, 1987). However, ratios of embryonic to after-hatch effects from studies of captive birds are likely to underestimate the relative importance of after-hatch effects because the after-hatch observation period is truncated (only six days in the latter study). In addition captive hatchlings are not exposed to real-world stressors such as predators and weather that could interactively mediate the demographic effect of selenium-induced debility of hatchlings. At Kesterson Reservoir, the estimated ratio of after-hatch effects to embryonic effects was 7:1, meaning that 88 percent of all reproductive impairment occurred after hatching (Ohlendorf, 1989). Because most NIWQP sampling sites were not as contaminated as Kesterson, applying the estimated ratio of effects at Kesterson to NIWQP data may overestimate the average after-hatch effects if the ratio is exposure dependent. Thus, a ratio of 3.5:1 for after-hatch to embryonic losses, intermediate between the captive-bird and Kesterson data, is used here. Therefore, the projected overall reproductive effects for the NIWQP study areas is 0.3-percent selenium-induced egg inviability among otherwise-viable eggs and an additional 1.05-percent selenium-caused mortality of hatchlings. Comparable projections for the effect sites would be 1.2-percent selenium-induced egg inviability among otherwise-viable eggs and an additional 4.2-percent selenium-caused mortality of hatchlings. Because neither egg inviability nor early hatchling death is likely to represent compensatory mortality (Hill, 1984, 1988), and because embryonic and after-hatch losses would be additive, they were combined herein and, for the sake of interpretive simplicity, equated to about 1.4-percent and 5.4-percent selenium-induced depression in nest success for the overall NIWQP and effect-site data sets, respectively.

As Terborgh (1989) reported with regard to the effects of cowbird parasites on clutches of prairie warblers (*Dendroica discolor*), an avian population's ability to tolerate even low rates of reproductive impairment from evolutionarily novel sources (such as anthropogenically mobilized contaminants) is strongly contingent on the extent to which the population demographically has adjusted to prior causes of reproductive failure, such as nest predation. The results from a study of prairie warblers in Indiana (Nolan, 1978) indicate the normal annual rate of adult mortality was about 35 percent and about 3.4 fledglings normally were produced per successful nest. Having normal nest predation of just less than 80 percent, this population just exceeded its demographic break-even point of about 20-percent nest success. Exposed to relatively high natural losses to nest predators, this population had adjusted demographically to produce a small surplus of young recruits. Human-caused modifications of the warblers' habitat caused them to become newly susceptible to cowbird parasites (an evolutionarily novel source of reproductive impairment for the warblers). About 24 percent of the warbler nests were parasitized by the cowbirds and the parasitized nests produced only 0.9 fledglings each compared to the normal 3.4 fledglings per nest. Thus, 24 percent of the 20 percent of nests not destroyed by nest predators had their productivity reduced by 73.5 percent (from 3.4 down to 0.9 fledglings), meaning that normal nest success was reduced about 3.5 percent by cowbird parasites' effect on prairie warblers clutches (that is, 0.24 x 0.20 x 0.735 = 0.035). However, that relatively small effect was sufficient to push the population over the demographic break-even point (Terborgh, 1989).

The demographic break-even point for North American populations of ducks has been estimated at 15-percent nest success for mallards and northern pintails (Klett and others, 1988; Greenwood and others, 1995) and at 20 percent for gadwalls, blue-winged teals, and northern shovelers. Additionally, break-even rates of nest success 11.7 percent for mallards and 13.5 percent for pintails, based on demographic models for productivity, were presented by Johnson and others (1987) and Carlson and others (1993). The overall rate (1.4 percent) of selenium-induced depression in nest success projected for the NIWQP study areas would be demographically crucial only for duck populations that are within about 0.2 to 0.3 percent of their break-even points because only about 11.7 to 20 percent of the contaminant-induced losses would actually be expressed in populations that are near their break-even points [that is, 0.014 x 0.117 = 0.0016, and 0.014 x 0.20 = 0.0028]. The remaining contaminant losses would be demographically masked in nests that were doomed to fail anyway from predation and other noncontaminant causes. Similarly, the median selenium-induced depression of nest success projected for NIWQP effect sites (5.4 percent) would be demographically crucial only for duck populations that are within about 0.6 to 1.1 percent of the demographic break-even point.

Many waterfowl populations apparently were existing close to or even below their demographic break-even points during the mid-1960's through the mid-1980's, according to broad-based regional surveys of nest success for waterfowl. Based on data presented by Klett and others (1988) for that 20-year period, the overall regional nest success for different species of ducks in the prairie pothole region of the United States (Minnesota, North Dakota, and South Dakota) was estimated to be 11.1 percent for mallards, 18.9 percent for gadwalls, 17.9 percent for blue-winged teals, 21.1 percent for northern shovelers, and 11.5 percent for northern pintails. None of those five estimates is within 0.2 to 0.3 percent of estimated break-even points, the amount that would be demographically crucial given the 1.4-percent selenium-induced depression in nest success projected for all the NIWQP study areas. However, four of those five estimates are within 0.6 to 1.1 percent of an estimated break-even point, the amount that would be demographically crucial given the 5.4-percent selenium-induced depression in nest success projected for all the NIWQP effect sites. Greenwood and others (1995) pooled data for several species of ducks across many study sites in the prairie pothole region of Canada to estimate the regional rates of nest success for ducks: 17 percent in 1982, 15 percent in 1983, 7 percent in 1984, and 14 percent in 1985. One of those four estimates is within 0.2 to 0.3 percent of a demographic break-even point, and two are within 0.6 to 1.1 percent. Collectively, the mid-1960's to the mid-1980's was a period of declining regional populations of dabbling ducks in the prairie pothole regions in both Canada and the United States (Dickson, 1989). Thus, the overall rate of selenium-induced depression of nest success projected for the NIWQP would have been demographically crucial in one out of nine cases just discussed, and at a minimum would have added to prior demographic deficits in several cases. The median selenium-induced depression in nest success projected for the NIWQP effect sites would have been demographically crucial (sufficient to push populations over the demographic break-even point) in five out of the nine cases.

For North American ducks, low-quality nesting habitats—due primarily to agricultural conversion of high-quality habitats (Gilmer and others, 1982; Malecki and Sullivan, 1987)—and relatively dry climatic cycles during the mid-1960's to mid-1980's produced conditions that left ducks highly vulnerable to nest predators. Although noncontaminant factors bear the primary responsibility for depressing nesting success to near or below the demographic break-even point, even small contaminant effects can be demographically decisive under such conditions.

In summary, for ducks, the magnitudes of avian effects projected for the NIWQP were sufficient to be potentially crucial at a population level of analysis. This conclusion is especially relevant considering that ducks are substantially more sensitive to selenium exposure than stilts, yet herein the assessment of hen effects is based on a stilt standard of sensitivity. However, the NIWQP study areas can be assumed to represent a worse-than-average subset of all potential study areas in the Western United States.

Published reports on demographic modeling for shorebirds are scarce; however, Robinson and Oring (1997) provided enough information on demographic parameters for American avocets to estimate a demographic break-even point of about 42 percent for nest success. This estimate also should apply to black-necked stilts because stilt and avocet life-history parameters are similar (Johnsgard, 1981; Robinson and others, 1997; Robinson and others, 1999). Thus, the overall 1.4-percent selenium-induced depression in nest success projected for the NIWQP study areas would be demographically crucial for regional populations of avocets and stilts that are within about 0.6 percent of their demographic break-even point. Similarly, the median 5.4-percent selenium-induced depression for nest success projected for the NIWQP effect sites would be demographically crucial only for avocet and stilt populations that are within about 2.3 percent of the demographic break-even point. Regional surveys of nest success among avocets and stilts that are comparable in scope to the scientific studies cited for ducks have not been done. The most extensive regional survey of nest success among avocets and stilts was completed during 1987–89 in the Tulare Lake Bed area (U.S. Fish and Wildlife Service, unpublished data), where populations were monitored intensively at 16 sites across the 5,800-mi^2 basin. Regional nest success for stilts was measured at 50.8 percent with 95-percent confidence boundaries at 48.1 and 53.7 percent (based on a sample of 21,797 nest-exposure days). Regional nest success for avocets was measured at 63.3 percent with 95-percent confidence boundaries at 60.7 and 65.9 percent (based on a sample of 26,865 nest-exposure days). In neither of these instances would the median rates of reproductive effects projected for the NIWQP be demographically crucial. In contrast, the projected local effects rate for the Tulare Lake Bed area (16.2 percent; table 33) would be demographically crucial for a population within 6.8 percent of the break-even point. The lower end of the confidence interval for stilt nest success is only 6.1 percent greater than the break-even point. Thus, at a local scale, the basinwide population (or subpopulation) of stilts in this area is, at best, at the brink of a contaminant-induced push over the demographic edge.

The NIWQP selected only 26 areas for reconnaissance investigations out of the hundreds of irrigation-drainage facilities and national wildlife refuges constructed or managed by DOI. The true demographic risks for biota associated with irrigation-induced water pollution in the Western United States cannot be assessed until a truly random sampling of irrigation projects (including Federal, State, and private projects) is completed. The areas selected for investigation by NIWQP were not randomly selected, instead they were those believed most likely to have irrigation-induced contamination effects. Because of this, the NIWQP areas more likely represents the worst-case and are not typical of the Western United States Accordingly, the worst-case scenario for the Western United States does include biotic effects at a demographically meaningful level for taxa such as ducks that already have been pushed close to their demographic break-even point by other factors such as the increased susceptibility to nest predators associated with degraded nesting habitat. Even the worst-case median levels of contaminant effects could be tolerated by populations of ducks existing just modestly above demographic break-even points. This suggests the biotic risk to ducks could be addressed by reducing irrigation-induced water pollution but more effectively by restoring high-quality (more predator-safe) nesting habitat.

RELATION BETWEEN SELENIUM IN WATER, SEDIMENT, AND BIOTA

Determining the relation between selenium concentrations in water and biota is important for several reasons. It provides a way to evaluate whether a screening investigation is adequate or has missed evidence of contamination. In addition, it provides a way to assess whether water criteria are indeed protective of fish and wildlife.

The relation between selenium concentrations in water, bottom sediment, and crayfish tissue was examined. Sites where crayfish were collected were matched with sites where surface-water and bottom-sediment samples were collected and analyzed for selenium. As discussed in the section "Sampling-Site Agreement," p. 21, not all biological samples were collected at locations where water or sediment samples were collected. Samples of 123 crayfish representing 86 distinct populations were collected in the NIWQP study areas. At the 66 sites where both water and crayfish were sampled, only those sites that had water samples collected during April–July (51 of the 66 sites) were analyzed. Collection sites for 41 crayfish populations were matched with 37 bottom-sediment sites. The geometric-mean selenium concentration for each crayfish population was computed and matched with selenium measurements of water or bottom-sediment samples collected during April–July (fig. 46).

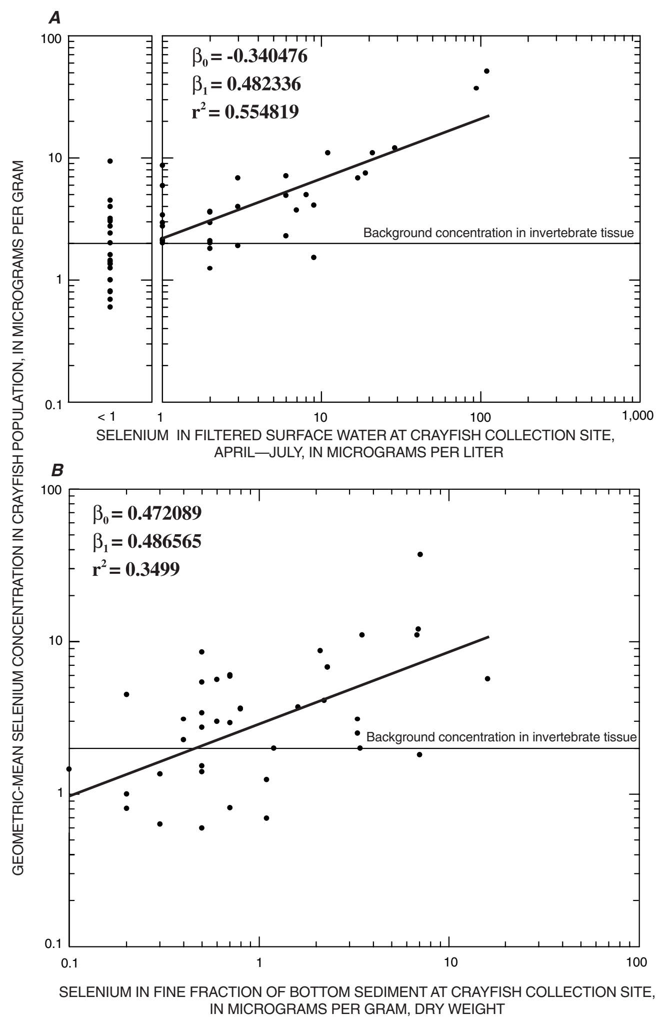


FIGURE 46. Relations among selenium concentrations in surface water and bottom sediment (<0.062-millimeter fraction), and invertebrate tissue [background concentration for invertebrate tissue from U.S. Department of the Interior (1998)].

Trends for increasing selenium concentration in crayfish tissue with increasing waterborne and bottom-sediment selenium are evident in figure 46. The large data scatter has several possible explanations: The amount of selenium absorbed may depend on the organic-carbon content of the bottom sediment, and data are insufficient to analyze this potential relation. Also, in an open system, crayfish can move into a contaminated area from a nearby uncontaminated area; the history of the organism collected is unknown. Also, because of survivor bias, in water bodies having high selenium concentrations, the most likely organisms to be collected are those having the lowest selenium burdens—the survivors.

Because selenium concentrations in water can vary rapidly from high to low in response to hydrologic factors (fig. 24), a single measurement of waterborne selenium could miss evidence of contamination. Most of the selenium in fish tissue results from uptake through diet rather than through water (Lemly, 1996c), however, one should expect a congruence between selenium concentrations in invertebrate and plant tissue and typical selenium concentrations in the water. If water samples do not show elevated selenium concentrations but tissue samples do, evidence of water contamination likely has been missed

The relation between selenium concentration in water and avian eggs was investigated to determine if the selenium concentration in water at the nesting site could be related to selenium concentrations in bird eggs. Of 804 surface-water sites where selenium was analyzed, 78 were matched with nesting sites where bird eggs were collected. Water samples commonly were not collected at the same time the eggs were collected, and selenium concentrations in the water can change greatly during a year (fig. 26), as discussed in the section "Temporal Changes in Selenium Concentrations," p. 58. Hence, only those nesting sites that had water samples collected during April–July (44 of the potential 78 matched sites) were used for this analysis because samples collected during this period more likely represent those to which breeding birds are exposed than would samples collected during August–March. Where multiple water samples were collected at a site, the earliest sample collected in the four-month period April–July was used to represent the selenium concentration in water at the nesting site.

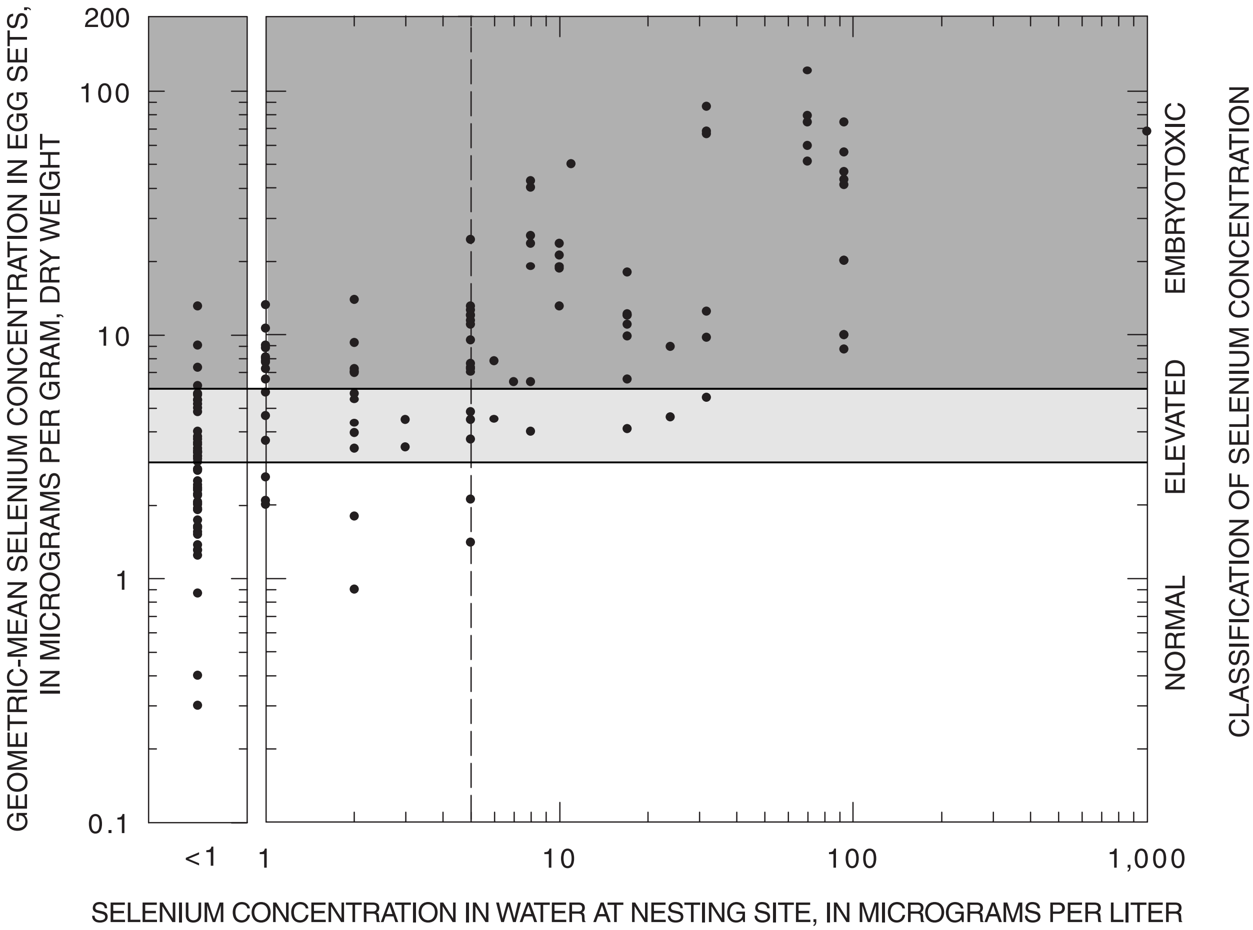
The eggs collected by the NIWQP investigators were grouped into sets that represent distinct breeding populations of birds. A total of 937 eggs from 31 species of birds were collected from nesting areas that could be matched with the 44 sites where water samples were collected during April–July. Analytical results for these 937 eggs were grouped into 158 sets, a set being a group of egg samples that represents a distinct breeding population of birds. For a set of eggs, a geometric-mean selenium concentration of 1 to 3 µg/g is considered normal. A geometric-mean selenium concentration exceeding 6 µg/g is considered embryotoxic because it is the threshold for embryotoxicity in black-necked stilts (Skorupa, 1998).

The relation between the selenium concentration in water at nesting sites and the geometric-mean selenium concentration in sets of eggs from NIWQP study areas is shown in figure 47. The graph shows that as the selenium concentration in water at a nesting site increases, the average selenium concentration in sets of bird eggs also increases. Of 65 sets of bird eggs collected from sites where the selenium concentration in the water equaled or exceeded 5 µg/L, the USEPA chronic criterion for selenium, 55 (85 percent of the sets) contained embryotoxic concentrations of selenium.

Only four of 54 sets of bird eggs had embryotoxic concentrations of selenium when selenium in the water was less than 1 µg/L. Nineteen of the 93 sets of bird eggs (20 percent) collected from sites where the selenium concentration in the water was less than 5 µg/L contained embryotoxic concentrations of selenium. The nineteen sets of eggs having embryotoxic selenium concentrations were from uncontaminated areas within a few miles of contaminated areas in the Kendrick Reclamation Project (*H*), middle Green River Basin (*N*), and Sun River area (*X*). Thus, even though eggs were from uncontaminated ponds and lakes, the hens may have been feeding in nearby contaminated areas.

Rankings of the study areas were used to answer two questions: (1) Do food organisms in areas where 25% of the water samples contain more than 5 µg/L selenium contain harmful amounts of selenium? (2) Are the organisms themselves from these areas harmed by the selenium? Rankings of the data, rather than the data itself, were used to reduce the effects of scale, sample bias, and extreme values in the data. The data and the rankings for the study areas are presented in table 35.

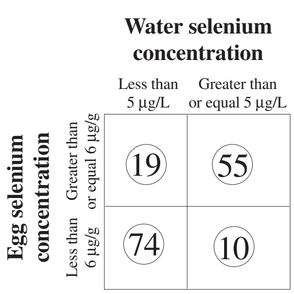
Twelve study areas were classified as selenium contaminated because the 75th percentile selenium concentration in surface water exceeded the USEPA chronic criterion for the protection of aquatic life, 5 µg/L (tables 15 and 35). Except for plants, in most cases median selenium concentrations in tissue samples exceeded 3 µg/g in those 12 areas. Three µg/g in tissue is used as a guideline because it is a toxic threshold for selenium in aquatic food-chain organisms consumed by fish and wildlife (Lemly, 1996c). A plot of rankings (fig. 48*A*) indicates that the median selenium concentration in plant tissue exceeded 3 µg/g in only 4 of the 12 study areas classified as contaminated. The median selenium concentration in tissue from aquatic invertebrates and fish exceeded 3 µg/g in most of the 12 areas (fig. 48*B*, *C*). In most cases the median selenium concentration in tissue was less than 3 µg/g in areas where the 75th percentile selenium concentration in surface water was less than 5 µg/L (fig. 48*B*, *C*).



EXPLANATION

— — — - U.S. Environmental Protection Agency (1987) chronic criterion for selenium in water

● Data points for egg set



Matrix of egg setsÑShowing number of egg sets per quadrant (as defined by U. S. Environmental Protection Agency chronic criterion and embryotoxic concentration)

D(y)=67.4, 1 df
$P<10^{-9}$

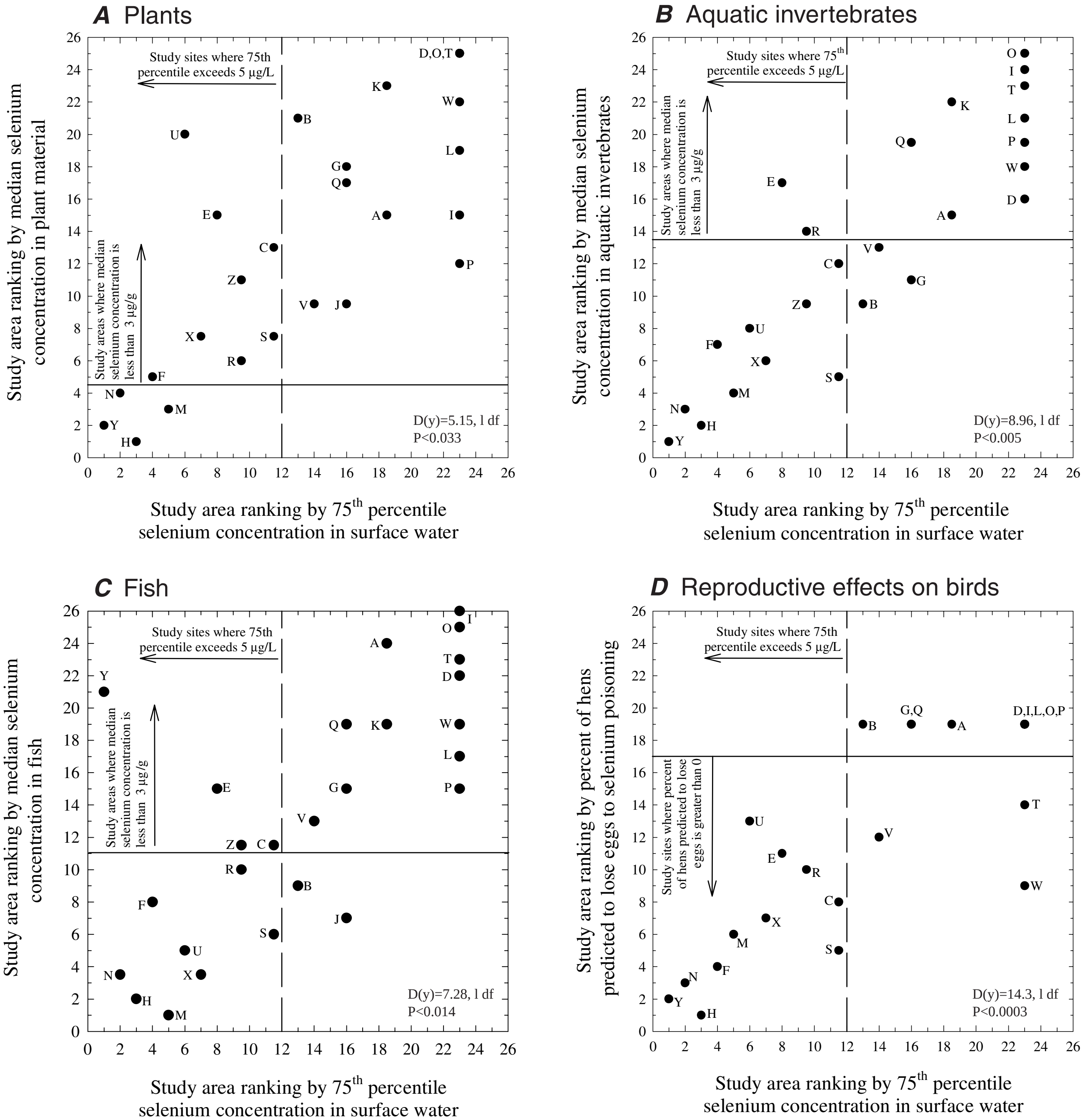
FIGURE 47. Relation between selenium concentrations in surface water at nesting site and in sets of avian eggs, during April–July 1987–92.

TABLE 35. *Study-area rankings, summary statistics for selenium concentrations in water, plants, aquatic invertebrates, and fish, and reproductive effects on birds.*

[Abbreviations and symbols: µg/L, microgram per liter; µg/g, microgram per gram (dry weight); <, less than; -, not determined or not applicable]

Identifier[1]	Name	Selenium in surface water[2]		Selenium in plants[3]		Selenium in aquatic invertebrates[3]		Selenium in fish[3]		Reproductive effects on birds[4]	
		Study area rank	75th percentile concen-tration (µg/L)	Study area rank	Median concen-tration (µg/g)	Study area rank	Median concen-tration (µg/g)	Study area rank	Median concen-tration (µg/g)	Study area rank	Percent hens loosing eggs to selenium poisoning
A	American Falls Reservoir, Idaho	18.5	1.0	15	0.85	15	2.8	24	1.3	19	0
B	Angostura Reclamation Unit, South Dakota	13	4.5	21	0.5	9.5	3.7	9	4.5	19	0
C	Belle Fourche Reclamation Project, South Dakota	11.5	5	13	0.9	12	3.2	11.5	2.8	8	2
D	Columbia River Basin, Washington	23	<1	25	<1.2	16	2.2	22	1.4	19	0
E	Dolores–Ute Mountain area, Colorado	8	7.0	15	0.85	17	2.0	15	2.4	11	1.1
F	Gunnison River Basin–Grand Valley Project, Colorado	4	35	5	1.7	7	4.8	8	5.8	4	8.5
G	Humboldt River area, Nevada	16	2.0	18	0.7	11	3.5	15	2.4	19	0
H	Kendrick Reclamation Project, Wyoming	3	64	1	7.3	2	28	2	8.8	1	55.6
I	Klamath Basin Refuge Complex, California–Oregon	23	<1	15	0.85	24	0.48	26	0.7	19	0
J	Lower Colorado River valley, California–Arizona	16	2.0	9.5	1.2	--	--	7	6.1	--	--
K	Lower Rio Grande valley, Texas	18.5	1.0	23	0.4	22	0.90	19	1.7	--	--
L	Malheur National Wildlife Refuge, Oregon	23	<1	19	0.6	21	1.4	17	1.9	19	0
M	Middle Arkansas River Basin, Colorado–Kansas	5	10	3	5.4	4	6	1	9.7	6	2.6
N	Middle Green River Basin, Utah	2	73	4	3.9	3	9.0	3.5	7.7	3	8.6
O	Middle Rio Grande, New Mexico	23	<1	25	<0.4	25	0.45	25	1.0	19	0
P	Milk River Basin, Montana	23	<1	12	0.95	19.5	1.6	15	2.4	19	0
Q	Owyhee–Vale Reclamation Project areas, Oregon–Idaho	16	2.0	17	0.8	19.5	1.6	19	1.7	19	0
R	Pine River area, Colorado	9.5	6.0	6	1.6	14	2.9	10	4.4	10	1.2
S	Riverton Reclamation Project, Wyoming	11.5	5.0	7.5	1.3	5	5.8	6	6.2	5	2.9
T	Sacramento Refuge Complex, California	23	<1	25	<1.2	23	0.68	23	1.4	14	0.2
U	Salton Sea area, California	6	8.0	20	0.58	8	4.6	5	7.4	13	0.7
V	San Juan River area, New Mexico	14	3.0	9.5	1.2	13	3.1	13	2.6	12	0.9
W	Stillwater Wildlife Management Area, Nevada	23	<1	22	0.42	18	1.7	19	1.7	9	1.9
X	Sun River area, Montana	7	7.5	7.5	1.3	6	4.9	3.5	7.7	7	2.3
Y	Tulare Lake Bed area, California	1	265	2	6.0	1	41	21	1.6	2	16.2
Z	Vermejo Project area, New Mexico	9.5	6.0	11	1.0	9.5	3.7	11.5	2.8	--	--

[1] Used in figure 2 to show locations of study areas.
[2] Concentrations and ranking from table 15.
[3] Concentrations and rankings from data presented in figure 28.
[4] Percentages and rankings from table 33.



EXPLANATION

C● **Data point for sampling site National Irrigation Water Quality Program study area**ÑLetter indicates study area

FIGURE 48. Relation between study-area rankings for selenium in water and plants, water and aquatic invertebrates, water and fish, and water and reproductive effects on birds.

In the 23 study-areas where bird eggs were collected, selenium contamination of surface water is significantly associated with hens losing eggs to selenium poisoning (fig. 48*D*). For 11 areas the 75th-percentile of selenium concentrations in surface water exceeded 5 µg/L and in all of those areas some hens were predicted to lose eggs to selenium poisoning. For 12 areas the 75th-percentile of selenium concentrations in surface water were less than 5 µg/L and in only 3 of those areas hens were predicted to lose eggs to selenium poisoning.

In some cases selenium concentrations in water were not congruent with selenium concentrations in tissue or the presence of biological effects. This can be the result of sample bias or locations of sampling sites for water and tissue samples not matching. For example, all of the fish collected during the Tulare Lake Bed area (*Y*) reconnaissance investigation were from irrigation canals and creeks, but most of the water samples and all of the plant, invertebrate, and bird samples were collected from selenium-contaminated evaporation ponds. In the Stillwater Wildlife Management Area (*W*), the eggs with the highest selenium concentrations are from a small pond distant from the main study area. Eggs from this pond comprise one-third of the bird eggs collected from the study area; however, less than 4 percent of the water samples were collected near that pond.

The rankings analysis indicates that most food organisms, particularly aquatic invertebrates and fish, contain potentially harmful amounts of selenium in study areas where selenium concentrations in more than 25 percent of the water samples exceed 5 µg/L. The rankings analysis also indicates that hens are losing eggs to selenium poisoning in all those study areas where selenium concentrations in more than 25 percent of the water samples exceed 5 µg/L. These results suggest that areas where selenium contamination of the food chain and loss of eggs to selenium poisoning is occurring may be identified using the same methods developed to identify areas where selenium contamination of water is likely to occur. The map of areas susceptible to irrigation-induced selenium contamination (fig. 34), which is based solely on physical data, identifies as susceptible 11 of 13 areas where the median selenium concentration in aquatic-invertebrates tissue exceeds 3 micrograms per gram and 7 of 10 areas for fish. Of the 14 areas where hens were predicted to lose eggs to selenium poisoning, 11 were identified as being susceptible to irrigation-induced selenium contamination.

SUMMARY AND CONCLUSIONS

NIWQP was created out of concern by the U.S. Congress and environmental groups that irrigation-induced contamination, which resulted in the collapse of the warm-water fishery and death and deformities of birds at Kesterson Reservoir in California in the 1980's, could happen elsewhere in irrigated areas of the United States. From 1986 through 1993, 26 areas for which the U.S. Department of the Interior is responsible were investigated for irrigation-induced contamination. In 1992, a NIWQP data-synthesis project was begun to identify factors common to contaminated areas. The main approach was to create a data base of information collected during investigations of the 26 NIWQP areas and to analyze the compiled data.

Selenium was the contaminant most often associated with irrigation in the areas investigated by NIWQP. Selenium concentrations in more than 40 percent of the surface-water samples exceeded 5 micrograms per liter, the USEPA chronic criterion for the protection of aquatic life. The study areas were not randomly selected. Many of the study areas were selected because of known or suspected selenium contamination and, thus, it is not surprising that a large percentage of the selenium samples exceeded the criterion.

Selenium, however, was not the only contaminant of concern. In some areas, concentrations of boron and molybdenum in surface water greatly exceeded criteria for the protection of aquatic life. Arsenic concentrations in surface water rarely, if ever, exceeded the chronic criterion for the protection of aquatic life; however, in four areas, the median arsenic concentration exceeded the current drinking-water MCL of 10 micrograms per liter and in 7 areas 25 percent or more of the samples exceeded the MCL. Except for DDT, pesticides in water rarely exceeded the aquatic-life criteria. Of the samples analyzed for total DDT, 21 percent exceeded the aquatic-life criterion; however, almost all the samples that exceeded the criterion were from a single study area.

Degradation of ground-water quality as a result of irrigation practices is a common occurrence. In some study areas, shallow domestic wells are the principal source of drinking water for individual households; however, most of the ground-water sites sampled by the NIWQP are not used as sources of drinking water. In 3 of the 13 study areas where samples were collected, selenium concentrations exceeded the MCL in more than 50 percent of the ground-water samples. Arsenic concentrations in 22 percent of the ground-water samples equalled or exceeded the current drinking-water MCL; however, almost all these samples were from a single area in Nevada. The median uranium concentration in ground water exceeded the MCL in two of ten areas, and individual samples exceeded the criterion in four of the areas.

Except for molybdenum, selenium and uranium, trace elements in bottom sediment generally did not exceed the upper limit of the qualitative sediment guideline for the Western United States. Selenium is the only trace element for which ecological sediment guidelines are used and selenium concentrations commonly exceeded that guideline of 2 micrograms per gram. DDE, a degradation product of DDT, was found in 81 percent of the samples of bottom sediment and in all 21 study areas where sediment was analyzed for pesticides.

In the NIWQP studies, certain contaminants were typically found associated. Such association indicates that they had similar sources or processes controlling their concentrations. Selenium was associated with sulfate, indicative of derivation from sulfide-containing sediments. Selenium contamination in an area was not correlated with contamination by arsenic, boron, or molybdenum. However, elevated selenium concentrations commonly were associated with elevated uranium concentrations. Boron and molybdenum commonly were found together. High concentrations of these elements were associated with high chloride concentrations, which indicate that evaporative processes were occurring. Contamination by arsenic is not associated with contamination by any other trace element.

Contaminant concentrations can have a wide range within a study area. Concentration ranges of arsenic, boron, molybdenum, selenium, and uranium all exceeded two orders of magnitude in some areas. Within the Kendrick Reclamation Project in Wyoming and the middle Green River Basin in Utah, selenium concentrations in surface water ranged from less than 1 to more than 5,000 micrograms per liter. Such a wide range means that chance combinations of flow and ground-water movement, local geology, and nearness to irrigated fields may result in uncontaminated samples being found even within contaminated areas.

Criteria for the protection of aquatic life have not been developed for boron and molybdenum by USEPA but may be needed to protect wildlife. Data collected by the NIWQP indicate that concentrations of these elements commonly exceeded levels at which adverse effects on wildlife may be expected. The State of California has developed aquatic-life criteria for boron and molybdenum, but such criteria are not used in all States. If the criteria developed for use in California are sound, then wildlife in other States likely are being exposed to toxic concentrations of boron and molybdenum as well.

Although water-quality standards and biological criteria generally were developed by using concentrations in whole (unfiltered) water, concentrations in filtered-water samples are nearly the same as concentrations in unfiltered samples for arsenic, boron, molybdenum, and selenium for concentrations greater than about 10 micrograms per liter. In the range of 1 to 10 micrograms per liter there may be a tendency for unfiltered arsenic concentrations to be greater than filtered concentrations. For selenium, however, the data suggest differences from equality in that range result from analytical imprecision and not a general tendency for unfiltered concentrations to be greater than filtered concentrations. This similarity suggests that contaminant concentrations measured in filtered samples can be compared to criteria developed by using whole-water samples. The equality of total-and filtered-selenium concentrations may not hold in lentic, nutrient-rich waters because in such settings algae can bioaccumulate large amounts of selenium.

Selenium was the trace element that most commonly exceeded USEPA criteria for the protection of aquatic life and was chosen to be the major focus of this report. Of the 26 areas investigated by the NIWQP, 12 were classified as selenium contaminated because selenium concentrations exceeded 5 micrograms per liter (the USEPA chronic criterion for the protection of aquatic life) in more than 25 percent of the surface-water samples.

Confirmed by data from the NIWQP, the association of selenium and sulfide minerals in geologic formations of Cretaceous age has been known since the 1930's. Median sulfate and selenium concentrations in NIWQP study areas showed positive correlations. Cretaceous geologic units were found to be associated with all 12 areas where selenium concentrations exceeded 5 micrograms per liter in more than 25 percent of the surface-water samples. Rocks of Cretaceous age are commonly seleniferous and are regionally the most important geologic source of selenium even though they are not the only seleniferous rocks. These rocks form the bedrock in more than 17 percent of the land area of the Western United States. Of the 26 study areas, 8 had no direct or indirect association with Upper Cretaceous sedimentary rocks and were not classified as selenium contaminated.

Local geologic sources of selenium are not the only important sources of selenium. Selenium can be imported into an area in irrigation water. An example of this occurs in the Imperial Valley/Salton Sea area in California. Colorado River water used for irrigation in the Imperial Valley contains concentrations of selenium only slightly less than Federal water-quality criteria because of irrigation drainage and natural runoff from seleniferous rock units in Colorado, Utah, and New Mexico. In other areas, discharges of selenium from oil-field and mine-pit-dewatering operations may result in selenium contamination when the effluent from such operations mixes with water that is used for irrigation downstream.

The climatic setting is important because once selenium is mobilized by application of irrigation water, the aridity of the area largely determines whether toxic concentrations of selenium result. Selenium concentrations in ground water in arid areas can become elevated because there is less infiltration of precipitation to dilute the selenium and because there are higher evapotranspiration rates. Evapotranspiration consumes water which increases selenium concentrations in the remaining soil and ground water. Two indices of aridity were compared—precipitation and the ratio of evaporation to precipitation. The relation between selenium concentrations and the ratio of evaporation to precipitation was more significant than the relation between selenium and precipitation alone. In those NIWQP study areas where irrigated lands overlie Upper Cretaceous sedimentary bedrock, and where the ratio of evaporation to precipitation exceeded about 3.0, selenium concentrations exceeded the USEPA chronic criterion in more than 25 percent of surface-water samples.

Whether water bodies are terminal or flow-through systems is important because selenium is not removed by flushing from terminal lakes. Although the presence of terminal water bodies of itself does not cause selenium problems to develop, if the geologic and climatic setting of an area are conducive to selenium contamination, then the presence of terminal water bodies is likely to make the selenium problem worse. As selenium loads are transported into a terminal water body, evaporation gradually increases the selenium concentration. In flow-through systems, the selenium load is moved through either continuously or episodically, thereby ameliorating existing selenium problems or decreasing the potential for selenium problems.

Geologic and climatic data for the Western United States were incorporated into a geographic information system to produce a map identifying areas susceptible to irrigation-induced selenium contamination. Areas are considered susceptible where marine sedimentary rocks form the bedrock in and near the area and where the evaporation rate is more than 2.5 times the precipitation rate. The map, which is based solely on physical data, may be useful in identifying areas where selenium contamination of the food chain and loss of eggs to selenium poisoning are occurring. The map identifies as susceptible 11 of 13 areas where the median selenium concentration in aquatic-invertebrates tissue exceeds 3 µg/g. In addition, the map identifies as susceptible 7 of 10 areas where the median selenium concentration for fish exceeds 3 µg/g. Of the 14 areas where hens were predicted to lose eggs to selenium poisoning, 11 were identified as being susceptible to irrigation-induced selenium contamination.

The potential for selenium contamination can change depending on climatic conditions. Some areas may not have selenium-contamination problems under normal conditions, but contamination may occur during drought years. Selenium becomes concentrated in ground and drain water because less water is available for dilution and evapotranspiration rates are higher. In addition, results of investigations to determine whether contamination actually is occurring may be misleading if sampling is done during wet periods when the selenium has been diluted temporarily.

In biological tissues, arsenic, boron, cadmium, copper, mercury, molybdenum, selenium, zinc, and DDE were identified as the contaminants of greatest concern by reconnaissance and detailed investigations. For avian eggs, tabulated toxic exceedance rates for each contaminant of greatest concern clearly showed that selenium was the most hazardous constituent associated with irrigation drainage in NIWQP study areas.

Selenium concentrations in biota were compared to concentrations that have been demonstrated to have adverse effects on similar species (the effect level) or to have adverse effects on another species if the contaminated biota are consumed (the dietary effect level). Twenty-five percent of the plant samples had selenium concentrations exceeding the dietary effect level, whereas 57 percent of the invertebrate samples and 61 percent of the fish samples exceeded that level. Of the more than 2,000 bird eggs collected, 44 percent had selenium concentrations exceeding 6 µg/g, a threshold value for reproductive effects. In 14 of the 26 NIWQP study areas, selenium concentrations in eggs from some populations of birds contained sufficient selenium to cause reduced hatchability of the eggs. Selenium-caused deformities of bird embryos were found in 4 of the 26 study areas.

Eggs from 54 populations were collected from nesting sites where the selenium in the water during April–July was less than 1 µg/L and only four populations contained embryotoxic concentrations. Eggs from 93 populations of birds were collected from nesting sites where the selenium concentration in the water during April–July was less than 5 µg/L, which is the USEPA chronic criterion for the protection of freshwater aquatic life. Nineteen of the 93 populations (20 percent) contained embryotoxic concentrations of selenium in the eggs. Eggs from 65 populations of birds were collected from nesting sites where the selenium concentration in the water during April–July was 5 µg/L or more, and 55 of those 65 populations (85 percent) had eggs that contained embryotoxic concentrations of selenium.

Eggs were sampled from 34 species of birds belonging to 10 orders. Nearly all the eggs collected come from aquatic species of birds, with American coots, mallards, and American avocets being the three species most frequently collected. Of the 34 species, at least one set of eggs from 16 species had a geometric-mean selenium concentration of at least 12.5 µg/g, a high-risk threshold. All three species of grebes yielded at least one set of high risk eggs, as did four of five species of shorebirds and five of eleven species of waterfowl. Egg-set data were examined to determine if some feeding guilds are more at risk to selenium poisoning than others. Analysis of data for waterbird eggs from study areas where the 75th percentile selenium concentration in surface water exceeded 5 µg/L suggests that herbivorous birds bioaccumulate less selenium than insect- and fish-eating birds. Selenium concentrations for 39 percent of the egg sets from herbivorous birds fell in the normal range (less than 3 µg/g) while only 7 and 0 percent, respectively, of egg sets from insect-and fish-eating birds fall in the normal range. Although herbivorous birds may be at less risk, it does not appear that any waterbird feeding guilds are particularly well buffered from exposure to selenium contamination.

For a quantitative risk assessment, avian and fish eggs are optimal as risk metrics. NIWQP biologists rarely sampled fish eggs; however, avian eggs were sampled extensively. Unlike the other extensively sampled biotic tissues (whole body fish or avian livers), avian eggs are not compromised by survivor bias. Examination of multielement-response data for the San Joaquin Valley in California led to the conclusion that teratogenic response to in-egg selenium exposure was free of significant confounding interaction with other trace elements. Thus, the response curves for that valley should be applicable to most, if not all, the NIWQP study areas.

There was no evidence for site-specific teratogenic-response functions. However, these response functions were strongly taxon-specific: Stilts were two times and ducks four times as sensitive as avocets. Regardless of which avian sensitivity standard or response curve—duck (sensitive), stilt (intermediate), or avocet (tolerant)—was applied to the NIWQP data base, at least 75 percent of the NIWQP study areas were predicted to have insufficient avian exposure to selenium to induce embryo teratogenesis. The reliability of teratogenesis predictions were tested by power analysis and found to match the observed results for 13 of 14 NIWQP study areas that reported embryo assessment data.

On the basis of embryo inviability, which is a more sensitive response variable than teratogenesis, 14 of 23 NIWQP study areas were projected to be subject to at least some degree of selenium-induced reproductive depression among waterbirds. Overall, 19 hens per 1,000 (1.9 percent) were projected to be affected by selenium-induced embryo inviability. At projected effect sites (79 of the 161 individual sample sites), 39 hens per 1,000 (3.9 percent) were predicted to be affected by selenium-induced embryo inviability. About 10 percent of effect sites were projected to suffer effects of a magnitude equal to or greater than that observed at Kesterson Reservoir in California.

After discounting hen effect for only partial clutch loss and for the masking of contaminant losses by other sources of nest failure such as nest predation, and after adding projections for after-hatch effects of selenium exposure, the overall selenium-induced reproductive depression in NIWQP study areas was estimated to be equivalent to a 1.4-percent reduction from normal nesting success. A comparable estimate for NIWQP effect sites would be a 5.4-percent reduction from normal nesting success.

Regional surveys of nesting success among ducks in the prairie pothole regions of the United States and Canada revealed that duck populations commonly were existing near their demographic break-even points. Consequently, even the overall projection of only 1.4-percent selenium-induced depression in nest success derived from NIWQP data was large enough to be demographically crucial in one of nine comparisons with survey data. Thus, one out of nine regionally surveyed duck populations was close enough to the demographic break-even point that an additional 1.4-percent reproductive depression in surviving nests (or the equivalent 0.1- to 0.3-percent depression in nest success) would push the population past the break-even point. The effect-sites projection of 5.4-percent selenium-induced reproductive depression in surviving nests (or the equivalent 0.6- to 1.1-percent depression in nest success) was large enough to be demographically crucial in five of nine comparisons with the regional demographic status of duck populations.

The true demographic risks for biota associated with irrigation-induced water pollution within the Western United States cannot be assessed until a truly random sampling of irrigation projects (including Federal, State, and private projects) is completed. The areas selected for investigation by NIWQP were not randomly selected, instead they were those believed most likely to have irrigation-induced contamination effects. Because of this, the NIWQP areas more likely represents the worst-case and are not typical of the Western United States. Accordingly, the worst-case scenario for the Western United States clearly includes biotic effects at a demographically meaningful level for taxa such as ducks whose regional populations commonly appeared to be existing close to their demographic break-even point.

It is important to consider why duck populations in the Western United States are so near the demographic break-even point that even relatively small depressions in nesting success caused by selenium can be demographically crucial. For North American ducks, relatively dry climatic cycles and low quality nesting habitats—due primarily to agricultural conversion of high-quality habitats—have produced conditions that left ducks highly vulnerable to nest predators. Non-contaminant factors bear the primary responsibility for depressing nesting success to near or below the break-even point, nonetheless, under such circumstances, even small effects from contaminants can be crucial. However, even the worst-case median levels of contaminant effects could be tolerated by populations of ducks existing just modestly above demographic break-even points. This suggests the biotic risk to ducks could be addressed by reducing irrigation-induced water pollution but more effectively by restoring high-quality (more predator-safe) nesting habitat.

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