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Identification of Areas at Risk for Selenium Contamination in the Western United States

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ABSTRACT

The U.S. Department of the Interior (DOI) studied contamination induced by irrigation drainage in 25 areas of the Western United States during 1986-93. Comprehensive evaluation of data from these studies, which began in 1992, provides some clear preliminary results. Irrigation of areas associated with marine sedimentary rocks of Late Cretaceous age is likely to result in selenium concentrations in water that can be expected to adversely affect some organisms. If there is a source of selenium, the magnitude of selenium contamination in drainage-affected aquatic ecosystems is strongly related to the aridity of the area and whether there are terminal lakes and ponds where evaporation can concentrate selenium. Such geologic and climatic data for the Western United States were incorporated into a Geographic Information System (GIS) to produce maps identifying areas susceptible to irrigation-induced selenium contamination. Nine of the 25 DOI study areas lie within or adjacent to areas predicted to be susceptible. In six of these nine areas, the average concentration of selenium in avian eggs exceeded the threshold for toxicity in more than 25 percent of all populations sampled. In the other three areas, average selenium concentrations in eggs were commonly above the normal range.

KEYWORDS: Selenium, Irrigation Drainage, Water Quality, Avian Toxicity

INTRODUCTION

In 1983, incidents of mortality, congenital deformities, and reproductive failures in waterfowl and other water birds were discovered at Kesterson National Wildlife Refuge (NWR), western San Joaquin Valley, California. The cause of these adverse biological effects was deter mined to be selenium poisoning, where selenium was carried by irrigation drainage into areas used by wildlife (Ohlendorf and others, 1986). Because concerns were expressed by the U.S. Congress and environmental groups that irrigation drainwater might have adverse effects elsewhere in the Nation, the U.S. Department of the Interior (DOI) implemented the National Irrigation Water Quality Program (NIWQP) in 1985 (Deason, 1986).

The DOI has constructed, financed, or manages more than 600 irrigation or irrigation-drainage facilities and National Wildlife Refuges in the 17 Western States. During 1985-86, the NIWQP conducted a comprehensive screening of existing data for these DOI facilities that resulted in selection of 26 areas for on-site reconnaissance investigations. Studies are complete in 25 areas (fig.1), and in 9 of the areas, these investigations confirmed that irrigation drainage had caused significant harmful effects to human health, fish, and wildlife, or had otherwise impaired beneficial uses of the water. Subsequent detailed investigations by NIWQP were made to determine the extent, magnitude, causes, and effects of contamination problems in eight of these areas (***F***, ***H***, ***I***, ***N***, ***U***, ***V***, ***W***, and ***X***; fig. 1). The remaining area *(Y)* was studied in detail under a separate cooperative Federal and State program.

Previous investigators (Sylvester and others, 1988; Feltz and others, 1991; Presser and others, 1994) evaluated data for some of the study areas and identified several factors affecting the concentration of contaminants associated with irrigation drainage. Some of the more important factors are

- geologic sources of trace elements,
- arid to semi-arid climate, and
- topographically closed versus open basins.

Presser (1994, p. 447) summarized 11 biogeochemical processes involved in the transport of selenium from rock to waterfowl at Kesterson NWR. Many of these processes probably occur in the areas investigated by the NIWQP that were contaminated with selenium. In 1992, the DOI began a 4-year data-synthesis project to compile and evaluate data from the completed and ongoing NIWQP investigations. The overall objective of the data synthesis is to identify physiographic factors and biogeochemical processes associated with irrigation-induced contamination of water and biota in the Western United States. Because selenium was the contaminant that most frequently exceeded water-quality criteria, a secondary objective of the data synthesis addressed in this paper is to develop the ability to predict where irrigation drainage is likely to result in selenium contamination of water and biota.

Although many irrigation projects in the Western United States may be susceptible to irrigation-induced selenium contamination, scarcity of monetary resources means that complete investigations cannot be made of every irrigation-project area. This paper provides managers with a tool to identify areas where irrigation is likely to cause contamination. Resources can then be targeted effectively toward investigating the highest risk areas first.

MATERIALS AND METHODS

A comprehensive relational database was constructed that contains data collected during the reconnaissance and detailed investigations. Included in the database are physical and chemical data from analysis of more than 6,000 samples of surface water and ground water, more than 700 samples of bottom sediment, and more than 10,000 samples of biota. Also included are physiographic data describing the 25 study areas and individual data-collection sites.

Summary statistics of dissolved-selenium concentrations in water and avian eggs for the 25 study areas were generated using the database. Summary statistics of data that include censored values were estimated using probability-plotting methods (Helsel and Hirsch, 1992). The amount of selenium contamination in an area was ranked on the basis of the dissolved-selenium concentration at the 75th percentile for flowing and impounded surface waters within and downstream from irrigated areas. Data from flowing and impounded bodies of water were combined for this paper.

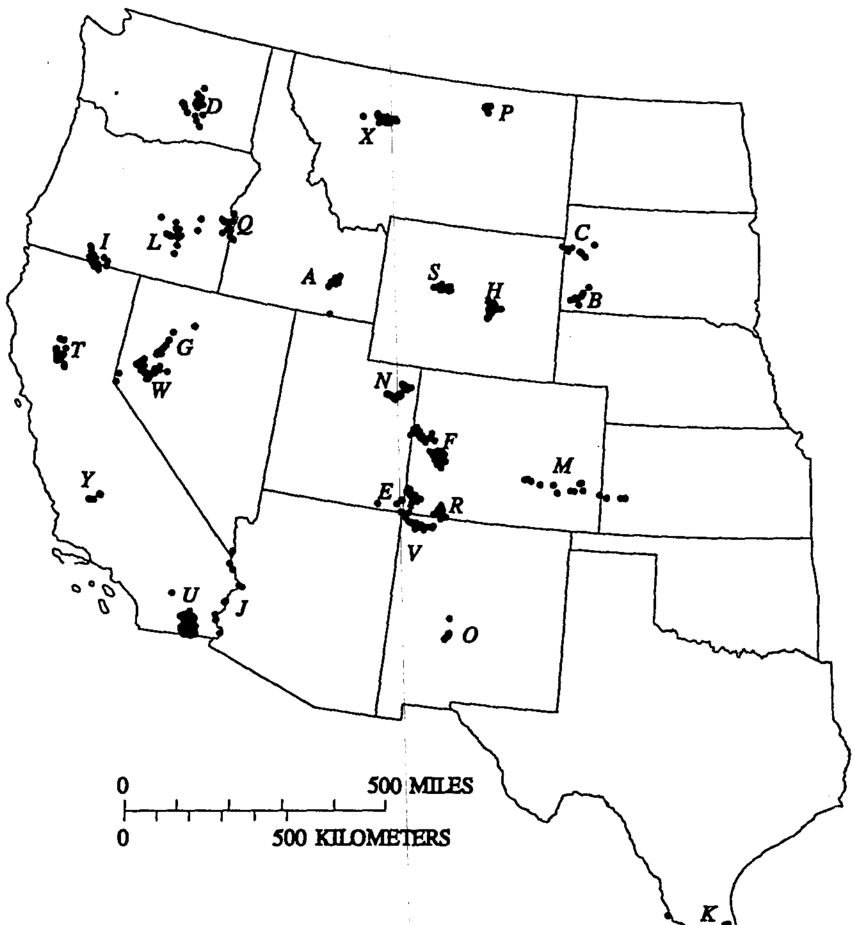


Figure 1. Location of study areas included in the National Irrigation Water Quality Program. See table 1 for names of study areas *A-Y*. Dots indicate individual data-collection sites.

Skorupa and Ohlendorf (1991) report that water containing 3-20 µg/L of total-recoverable selenium should be considered hazardous to some species of aquatic birds, depending on specific environmental conditions. For this report, avian toxicity was considered possible in areas where

25% or more of the surface-water samples from irrigated areas or downstream from them had dissolved-selenium concentrations exceeding 3 μg/L, the lower end of that range.

Avian eggs analyzed from the 25 study areas were grouped into 'sets.' A 'set' is a distinct group of samples that conceptually represents the eggs of a distinct breeding population of birds for a given site and year. A single egg or composite sample represents the set for some particular breeding populations of birds. The geometric mean of selenium concentrations (dry weight) for each set of avian eggs was calculated, and then the 75th-percentile concentration of the means was calculated for each of the NIWQP study areas.

Ohlendorf (1989) reported that the mean selenium concentration in sets of avian eggs from uncontaminated areas is about 1-3 μg/g dry weight. Skorupa and Ohlendorf (1991) reported that in avian eggs, mean selenium concentrations greater than 8 μg/g dry weight are associated with significantly reduced hatchability and that data from field samples indicate that the threshold for teratogenesis is between 13 and 24 μg/g. The NIWQP study areas were classified into three categories based on the 75th-percentile mean selenium concentration of the sets of avian eggs:

- *Normal*, selenium concentration less than 3 μg/g;
- *Elevated*, selenium concentration 3 to 8 μg/g; and
- *Embryotoxic*, selenium concentration greater than 8 μg/g.

Geology was generalized from King and Beikman's (1974) geologic map of the United States. The 25 study areas were classified into three categories:

- Areas where some irrigated land lies on Upper Cretaceous (uK), mainly marine, sediments;
- Areas where upland areas adjacent to irrigated land are uK, mainly marine, sediments; and
- Areas that are not associated with uK, mainly marine, sediments.

Areas also were classified by whether major sources of selenium are upstream from irrigated land. Selenium sources could include discharges from oil-field or mining operations or tributaries that pass over seleniferous material. For example, the source water for irrigation for the Salton Sea Area (***U***; fig. 1) is the Colorado River, which receives water from the Green River and San Juan River, both of which drain uK marine sediments many miles upstream from the Salton Sea.

The aridity of the study areas and their potential for evaporative concentration of drain-water was characterized by calculating an evaporation index: the ratio of annual free-water-surface evaporation to average annual precipitation. Free-water-surface evaporation rates for the 25 areas were determined from evaporation maps of the United States (Farnsworth and others, 1982). The average annual precipitation for each of the 25 areas was taken from results of individual DOI investigations. In two of the areas, Milk River Basin (***P***; fig. 1) and Riverton Project Area (***S***; fig. 1), all data were collected during a single month in a year when the precipitation was atypical. For those two areas, the precipitation during the year of data collection rather than the average annual precipitation was used to calculate the evaporation index.

Areas were classified hydrologically as open or closed basins depending on whether lakes or ponds that receive irrigation drainwater are terminal (that is, have no outlet) during non-flood years. Some of the lakes or ponds, such as the Salton Sea, are large, and others may be very small unnamed stockponds or impoundments. The size of the water body was not considered in the hydrologic classification.

RESULTS AND DISCUSSION

In 11 of the 25 areas, the dissolved-selenium concentration in 25% or more of the surface-water samples equaled or exceeded the U.S. Environmental Protection Agency (USEPA) chronic criterion for selenium for the protection of freshwater aquatic life, 5 µg/L (fig. 2, table 1) (U.S. Environmental Protection Agency, 1986). In 13 areas, the selenium concentrations in 25% or more of the surface-water samples equaled or exceeded the avian effect level, 3 µg/L. In seven areas, selenium concentrations in fewer than 25% of the surface-water samples exceeded the analytical reporting limit (1 µg/L), and in three areas, selenium was not detected in any surface-water sample.

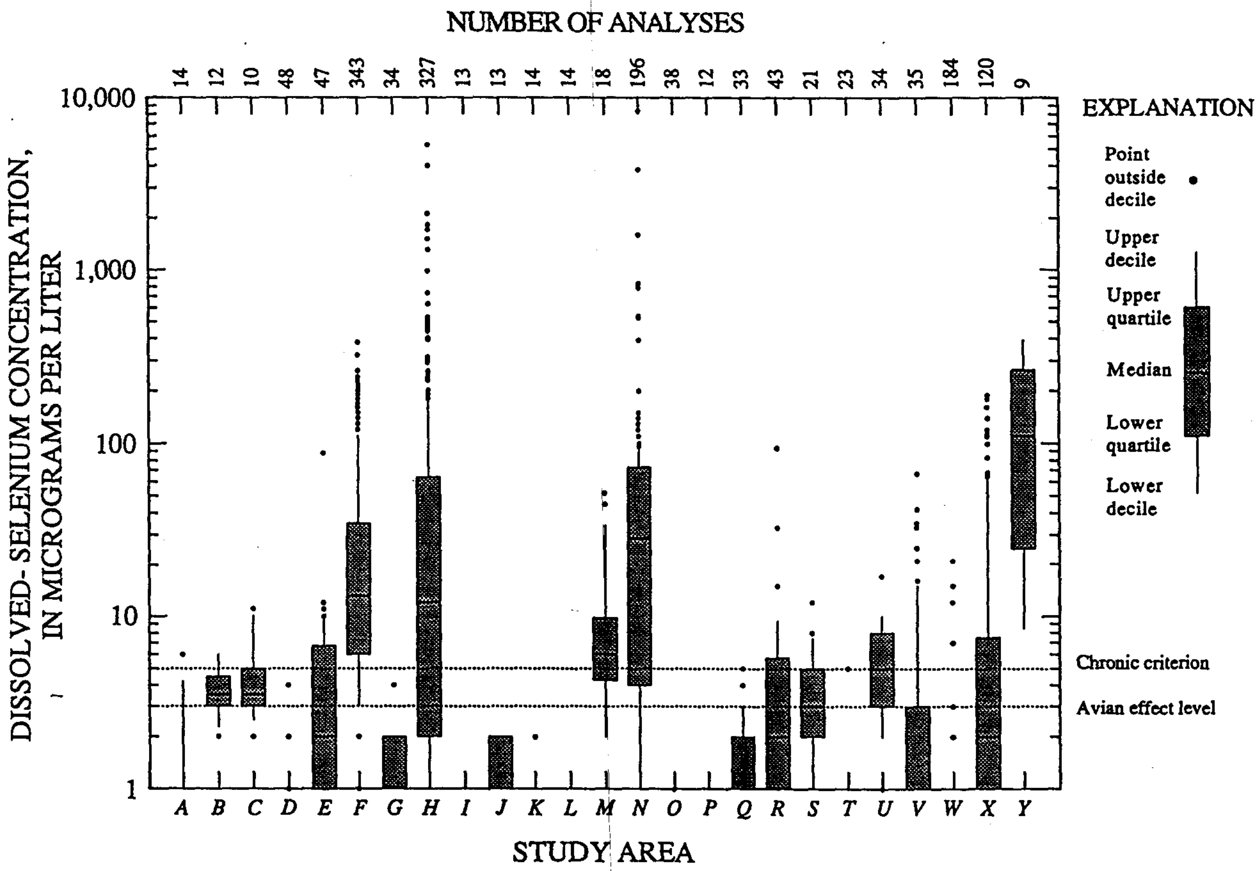


Figure 2. Statistical summary of selenium concentrations in surface water from National Irrigation Water Quality Program study sites. See table 1 for complete names of study areas *A*-*Y*. Chronic criterion from U.S. Environmental Protection Agency (1986), and avian effect level from Skorupa and Ohlendorf (1991).

In 7 of the 25 areas, 25% or more of the sets of avian eggs contained embryotoxic concentrations of selenium (table 1). In nine areas, 25% or more of the sets contained elevated concentrations of selenium. In seven areas, fewer than 25% of the sets, and in some instances none of the sets, fell outside the normal range. At two areas, avian eggs were not sampled.

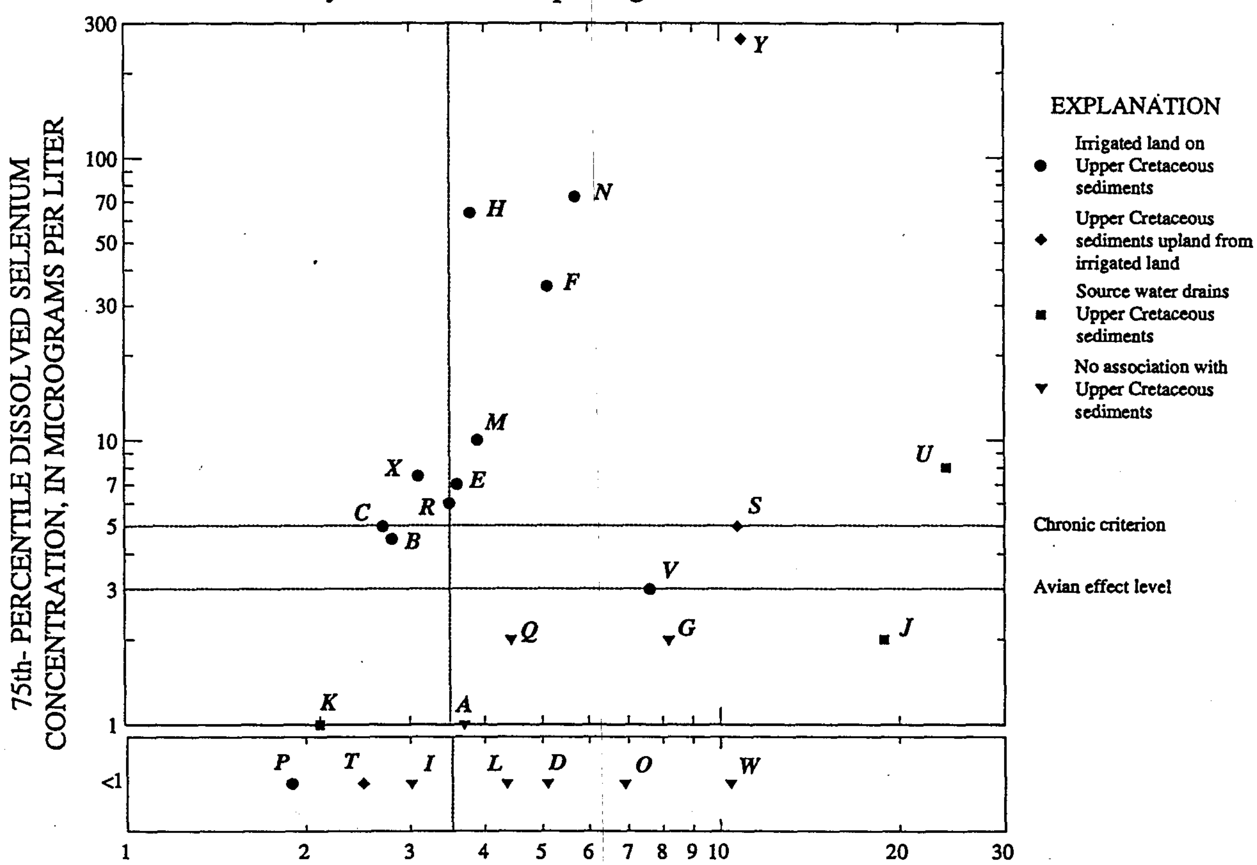
TABLE 1. Selenium concentration in surface water and number and classification of avian egg sets sampled at study areas of the National Irrigation Water Quality Program

Map ID. (fig. 1)	Study area	Selenium concentration (at 75th percentile, in μg/L)	Sets of avian eggs Number	Sets of avian eggs Classification
A	American Falls Reservoir, ID	1	7	Normal
B	Angostura Reclamation Unit, SD	4.5	2	Normal
C	Belle Fourche Reclamation Project, SD	5	5	Embryotoxic
D	Columbia River Basin, WA	<1	7	Normal
E	Dolores-Ute Mountain Area, CO	7	10	Elevated
F	Gunnison River Basin-Grand Valley Project, CO	35	48	Embryotoxic
G	Humboldt River Area, NV	2	5	Elevated
H	Kendrick Reclamation Project, WY	64	15	Embryotoxic
I	Klamath Basin Refuge Complex, CA-OR	<1	5	Normal
J	Lower Colorado River Valley, CA-AZ	2	0	—
K	Lower Rio Grande, TX	1	0	—
L	Malheur National Wildlife Refuge, OR	<1	13	Normal
M	Middle Arkansas River Basin, CO-KS	10	3	Elevated
N	Middle Green River Basin, UT	73	142	Embryotoxic
O	Middle Rio Grande Project, NM	<1	6	Normal
P	Milk River Basin, MT	<1	3	Normal
Q	Owyhee-Vale Reclamation Project, OR-ID	2	9	Elevated
R	Pine River Area, CO	6	10	Embryotoxic
S	Riverton Reclamation Project, WY	5	7	Embryotoxic
T	Sacramento Refuge Complex, CA	<1	6	Elevated
U	Salton Sea Area, CA	8	9	Elevated
V	San Juan River Area, NM	3	9	Elevated
W	Stillwater Wildlife Management Area, NV	<1	29	Elevated
X	Sun River Area, MT	7.5	126	Elevated
Y	Tulare Lake Bed Area, CA	265	132	Embryotoxic

The relations among selenium concentration in water, aridity, and geology are shown in figure 3. Eleven of the 25 areas contain land that lies on uK, mainly marine, sediments. In all but one of these areas, more than 25% of the surface-water samples in irrigated areas and downstream from them was 3 μg/L or more. Upper Cretaceous marine sediments are upland from three of the study areas, and in two of those areas more than 25% of the surface-water samples contain selenium concentrations exceeding 3 μg/L.

Knowing where selenium contamination does not occur is nearly as important as knowing where it does. Areas that are not associated with uK marine sediments are unlikely to have selenium contamination problems. Eight of the 25 areas are not associated with Upper Cretaceous rocks. In these areas, fewer than 25% of the samples had selenium concentrations exceeding 3 μg/L and in five of the eight areas fewer than 25% of the samples had selenium concentrations exceeding the analytical reporting limit (1 μg/L).

If a source of selenium exists, the amount of selenium contamination in an area is determined in large part by whether it has terminal lakes or ponds. Figure 3 shows that selenium concentration in areas associated with uK marine sediment increases with increasing aridity. The only apparent exception is the San Juan River Area (*V*; fig. 1). However, this is probably because of sample bias toward high discharge or mainstem river sites where selenium concentrations are usually less than the reporting limit.



EVAPORATION INDEX

Figure 3. Relation of dissolved-selenium concentration, aridity, and geology for National Irrigation Water Quality Program study areas. See table 1 for names of study areas *A-Y*. Chronic criterion from U.S. Environmental Protection Agency (1986), and avian effect level from Skorupa and Ohlendorf (1991).

Areas with very low evaporation indices are unlikely to have selenium contamination problems even if a source of selenium exists. The Milk River Basin (*P;* fig. 1) might be expected to be contaminated, because elevated concentrations of selenium have been reported in a stream in the area (Presser and others, 1994) and because it lies on seleniferous sediment. However, no selenium was detected in any of the NIWQP surface-water samples from this study area because the samples were collected during a flood year. The evaporation index for the area was calculated for the year of data collection and was the lowest of any of the 25 areas.

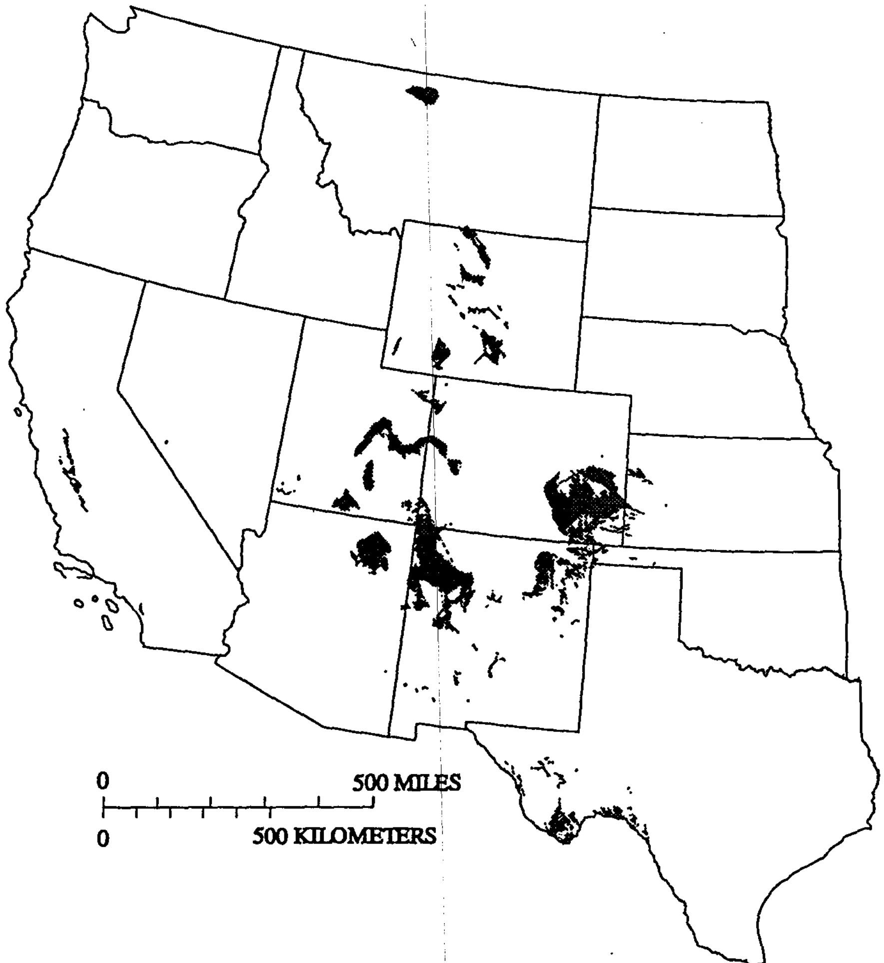


Figure 4. Areas in the Western United States susceptible to irrigation-induced selenium contamination. (Shaded areas indicate where the surficial rocks are Upper Cretaceous, mainly marine, sediments and the evaporation index is greater than 3.5.)

Areas with terminal lakes or ponds are especially at risk if a local source of selenium exists. Evaporation from terminal lakes can result in very high concentrations of dissolved selenium because, under normal circumstances, water does not flow through the lakes and flush out accumulated selenium. Concentration by evaporation is most common during drought periods of reduced water availability. Congenital deformities of waterfowl like those found at Kesterson NWR have been positively identified in 3 of the 25 areas (***H***, ***N***, and ***Y***; fig. 1), all of which have terminal lakes or ponds in areas where the soils are derived from uK sediments.

The results of this data synthesis indicate that areas in the Western United States susceptible to irrigation-induced selenium contamination problems can be identified using readily available geologic and climatic data (fig. 4). Geographic Information System (GIS) coverages were obtained that include annual precipitation, free-water-surface evaporation, and geology of the United States. The geologic coverage was used to create a map identifying uK marine sedi ments. A coverage of the areas where the evaporation index is greater than 3.5 was created by manipulating the evaporation and precipitation coverages. A value of 3.5 was used because, in most areas associated with uK marine sediments, the selenium concentration in more than 25% of the samples exceeds the USEPA chronic criterion if the evaporation index exceeds 3.5. A map identifying areas susceptible to irrigation-induced selenium contamination (fig. 4) was created by intersecting the coverages of uK sediments and evaporation index greater than 3.5.

About 130,000 square kilometers of land in the Western United States is identified as being susceptible to irrigation-induced selenium contamination. Maps have been prepared that show locations of Bureau of Reclamation project areas and National Wildlife Refuges in relation to areas susceptible to selenium contamination. Whether problem areas can be correctly identified by using the map was assessed by plotting the NIWQP study areas on the map. Nine of the 25 areas lie on or adjacent to areas mapped as susceptible to selenium contamination. The Skorupa and Ohlendorf (1991) value of 3 µg/L was exceeded in all nine areas; in eight of the nine areas, 25% of the surface-water samples equal or exceed the USEPA chronic criterion for selenium for freshwater aquatic life.

In six of the nine NIWQP areas that lie on or adjacent to mapped susceptible areas, the mean concentration of selenium in sets of avian eggs was embryotoxic in more than 25 percent of the sets that were sampled. In the remaining three areas, selenium concentrations in the sets were elevated well above the normal range, but rarely exceeded the embryotoxic threshold. Of the seven areas classified as embryotoxic in table 1, only the Belle Fourche Reclamation Project (*C*; fig. 1) did not lie on or adjacent to an area mapped as susceptible to selenium contamination.

Not all areas susceptible to selenium contamination can be identified using the map. The map fails to identify one area classified as embryotoxic, and three areas where the selenium concentration in more than 25% of the water samples exceeds the USEPA chronic criterion. This is because important hydrologic data about terminal ponds and upstream sources of selenium are not mappable. In the Sun River Area (*X;* fig. 1) and Belle Fourche Reclamation Project (*C*; fig. 1), the evaporation index is slightly less than 3.5, but terminal ponds are present. In the Salton Sea Area (*U;* fig. 1), uK marine sediments are absent but an upstream source of selenium exists.

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