DETAILED STUDY OF SELENIUM IN SOIL, REPRESENTATIVE PLANTS, WATER, BOTTOM SEDIMENT, AND BIOTA IN THE KENDRICK RECLAMATION PROJECT AREA, WYOMING, 1988-90

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U.S. BUREAU OF RECLAMATION, and the

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
acre	4,047	square meter
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	0.001233	cubic hectometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	2.54	centimeter
mile (mi)	1.609	kilometer
ounce, avoirdupois (oz)	28.35	gram
square mile (mi^2)	2.590	square kilometer

Temperature can be converted to degrees Fahrenheit (°F) or degrees Celsius (°C) by the following equations:

$$^{\circ}F = 9/5\ (^{\circ}C) + 32$$

$$^{\circ}C = 5/9\ (^{\circ}F - 32)$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from an adjustment of the first-order level nets of the United States and Canada, formerly called "Sea Level Datum of 1929."

Abbreviations used in this report:

cm	centimeter
g	gram
kg	kilogram
kg/d	kilogram per day
km	kilometer
m	meter
MCL	maximum contaminant level
mg/g	milligram per gram
mg/L	milligram per liter
ml	milliliter
mm	millimeter
p,p'-DDE	para, para'-dichlorodiphenyldichloroethylene
spp.	species
μg/d	microgram per day
μg/g	microgram per gram
μg/L	microgram per liter
μm	micron
μS/cm	microsiemens per centimeter at 25 degrees Celsius

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By Randolph B. See[1], David L. Naftz[1], David A. Peterson[1], James G. Crock[1] James A. Erdman[1], R.C. Severson[1], Pedro Ramirez, Jr.[2], and Joni A. Armstrong[2]

ABSTRACT

In response to increasing concern about the quality of irrigation drainage and its potential effects on fish, wildlife, and human health, the U.S. Department of the Interior formed an interbureau group to address related water-quality problems. The Kendrick Reclamation Project area (Kendrick area) was one of nine areas in the western United States that were assigned the highest priority for investigation. The magnitude, effects, and exposure pathways of selenium associated with irrigation drainage are summarized in this report. Trace elements and constituents other than selenium were evaluated but generally were not at concentrations considered harmful to wildlife or humans.

A geochemical survey of the rangeland to assess the importance of geological formations as a selenium source indicated that none of the native soil samples exceeded the 3.3 micrograms per gram (μg/g) maximum baseline for total selenium established in previous studies for soils from the Northern Great Plains. Selenium concentrations tended to be largest in soil derived from Cody Shale, but not uniformly so. In contrast, selenium concentrations in about 20 percent of the associated samples of big sagebrush exceeded the 1.1 μg/g maximum baseline established for this species in the western United States.

In a separate survey of the irrigated land, significant differences in concentrations of total selenium were detected in soil samples collected from the fields sampled, but only 2 of the approximately 200 soil samples contained selenium concentrations larger than the baseline. As with the big sagebrush results from the rangeland, some of the alfalfa samples from the irrigated fields had large selenium concentrations (as much as 25 μg/g). Alfalfa samples from about 15 percent of the irrigated fields contained selenium in excess of the 4 μg/g threshold, which is potentially hazardous to livestock if consumed over prolonged periods. Most of the alfalfa samples with large selenium concentrations were grouped in an area of 11 contiguous sections where there was selenium-enriched surface water and drainwater. Two fields that yielded alfalfa samples containing 25 and 15 μg/g selenium in 1988,

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yielded samples containing only 0.2 and 0.7 μg/g selenium in 1989. Differences in weather patterns and irrigation practices could account for this large observed difference in alfalfa selenium concentrations from one year to the next.

The major tributaries draining the Kendrick area account for an average of 52 percent of the total selenium discharge measured in the North Platte River downstream of Casper. The 4-day average selenium concentration in water samples from the North Platte River, which receives irrigation return flows, exceeded the U.S. Environmental Protection Agency's freshwater chronic aquatic life criterion of 5 micrograms per liter (μg/L) five times during a 50-day monitoring period in 1989. One sample downstream of Casper had a selenium concentration equal to the maximum contaminant level of 10 μg/L allowed under the current U.S. Environmental Protection Agency drinking-water regulations.

Based on selenium/chloride ratios, oxygen-18/oxygen-16, and deuterium/hydrogen ratios in water from Rasmus Lee and Goose Lakes (closed-basin systems), observed selenium concentrations could have been derived by natural evaporation of irrigation water without leaching of soluble forms of selenium from soil or rocks. Water samples from Thirtythree Mile Reservoir and Illco Pond (flow-through systems) showed considerable enrichment in selenium over evaporative concentration, presumably caused by leaching and desorption of selenium from soil and rock. Selenium-to-chloride ratios of irrigation drainwater collected from the Kendrick area indicate that dissolution and desorption of soluble forms of selenium from soils and rocks are the dominant processes in drainwater. Results of a Wilcoxon matched-pairs test for 43 paired drainwater samples collected during June and August 1988 indicated there was a statistically larger selenium concentration (0.01 significance level) during the June sampling period.

Large selenium concentrations in water samples from wetland sites in the Kendrick area were reflected in the aquatic food chain. Samples of muscle tissue from rainbow trout collected from portions of the North Platte River receiving irrigation-return flow had selenium concentrations exceeding levels known to cause reproductive failure and chronic selenium poisoning in fish. Samples of livers and eggs of aquatic birds nesting in the Kendrick area showed selenium concentrations larger than concentrations suspected of causing adverse reproductive effects.

INTRODUCTION

During the last several years, there has been increasing concern about quality of irrigation drainage--both surface and subsurface water draining irrigated land--and its potential effects on fish, wildlife, and human health. Large concentrations of selenium have been detected in subsurface drainage from irrigated land in the western part of the San Joaquin Valley in California (Gilliom and others, 1989). In 1983, incidences of mortality, birth defects, and reproductive failures in aquatic birds were discovered by the U.S. Fish and Wildlife Service at the Kesterson National Wildlife Refuge in the western San Joaquin Valley (hereinafter called Kesterson), where irrigation drainage was impounded. In addition to selenium, arsenic, heavy metals, and pesticide residues have been detected in several areas in the western United States that receive irrigation drainage.

Members of Congress, Federal and State agencies, and several environmental organizations interested in the general nature and extent of contaminant problems associated with irrigation drainage have requested information from the U.S. Department of the Interior (DOI). In October 1985, the DOI developed the Irrigation Drainage Program to address water-quality problems related to irrigation drainage for which the DOI may have responsibility.

The DOI prepared a management strategy, and the Task Group prepared a comprehensive plan for reviewing irrigation drainage concerns, subsequently identifying 19 areas that warranted reconnaissance investigations. The study areas were identified on the basis of three specific situations: (1) Irrigation or drainage facilities constructed or managed by the DOI; (2) National Wildlife Refuges that receive irrigation drainage; and (3) other migratory bird or endangered-species management areas that receive water from DOI-funded projects. The Task Group assigned the highest priority to nine of the areas identified (Sylvester and Wilber, 1989). The Kendrick Reclamation Project area, referred to as Kendrick area in this report, near Casper, Wyoming (fig. 1) was one of these areas.

Elevated concentrations of selenium were detected in samples of water, bottom sediment, and biota that were collected in or near the Kendrick area during the 1986-87 reconnaissance investigation (Peterson and others, 1988, p. 41). An evaluation of whether the large concentrations were localized or widespread required additional information about the geochemical and biological processes controlling the mobility and availability of selenium and associated trace elements. An understanding of these processes is needed to evaluate the magnitude of potential toxicity problems and provide the data for any corrective measures that may be needed.

This study was conducted by an interbureau team composed of a scientist from the U.S. Geological Survey (USGS) as team leader, with additional USGS, U.S. Fish and Wildlife Service, and U.S. Bureau of Reclamation scientists representing several different disciplines. Funding for the study was provided by the U.S. Department of the Interior and the Wyoming Department of Environmental Quality.

Purpose and Scope

The purpose of this report is to summarize the results of the DOI study conducted during 1988-90 and related research in the Kendrick area on the (1) geologic extent, severity, magnitude, effects, and exposure pathways of selenium associated with irrigation drainage on water resources and biota and (2) provide the scientific understanding needed for development of reasonable alternatives to mitigate or resolve identified problems. Specific objectives of this report are to describe the following:

1. The magnitude and distribution of selenium in irrigated and nonirrigated soil and representative plants in and adjacent to the Kendrick area.

2. The magnitude and distribution of selenium in water from the North Platte River and its tributaries, and in water and bottom sediment in wetlands.

3. The seasonal variability in selenium loading to the North Platte River from the major irrigation-drainwater discharges and how these discharges affect the concentration of selenium in river water used as a municipal water supply by the city of Casper.

4. The magnitude and distribution of selenium in shallow ground-water and surface-water sources in the Kendrick area that are used as domestic or livestock water supplies.

5. The principal geochemical processes that affect the concentration of selenium in surface water and ground water and identify the important geochemical processes controlling selenium mobility.

6. The aquatic bird use of wetland areas.

7. The selenium concentrations in aquatic vegetation, aquatic invertebrates, fish, and aquatic birds; and evaluate whether concentrations could have potentially adverse physiological effects on fish, aquatic birds, or humans who regularly consume fish and aquatic birds.

8. The major food-chain pathways for bioaccumulation of selenium in selected fish and aquatic birds.

9. The major sources of selenium and factors contributing to selenium discharge from the Kendrick area.

This report focuses on selenium. It contains information on the onsite and laboratory methods used and an assessment of selenium variability and selenium sources in the soils, representative plants, water, bottom sediment, and biota. Analyses of the sample materials indicated that the main constituent of concern is selenium. Trace elements and constituents other than selenium were evaluated but, except for arsenic, boron, cadmium, mercury, and lead in selected biological samples, were assessed to be at concentrations not harmful to wildlife or humans.

Sampling efforts for irrigated soils and alfalfa, water, bottom sediment, and biota were concentrated in and adjacent to the Kendrick area. Additional samples of nonirrigated soil and big sagebrush were collected throughout the study area.

Previously published reports from this study discuss, in detail, selenium in soils and plants of the Kendrick area (Erdman and others, 1989), lateral and depth variability of chemical composition of Kendrick area soils (Severson and others, 1989a), and a listing of data and an assessment of the variability in trace element compositions of soils and plants at the Kendrick area (Severson and others, 1989b). A report listing physical, chemical, and biological data (See and others, 1992) has been prepared concurrently with this report.

Study Area

The study area is in Natrona County in central Wyoming (fig. 1). The Kendrick area is located west of the city of Casper and bounded by the North Platte River on the southeast, Casper Creek on the northeast, and Casper Canal on the north and west (fig. 1). The Kendrick area is about 188 mi^2; however,

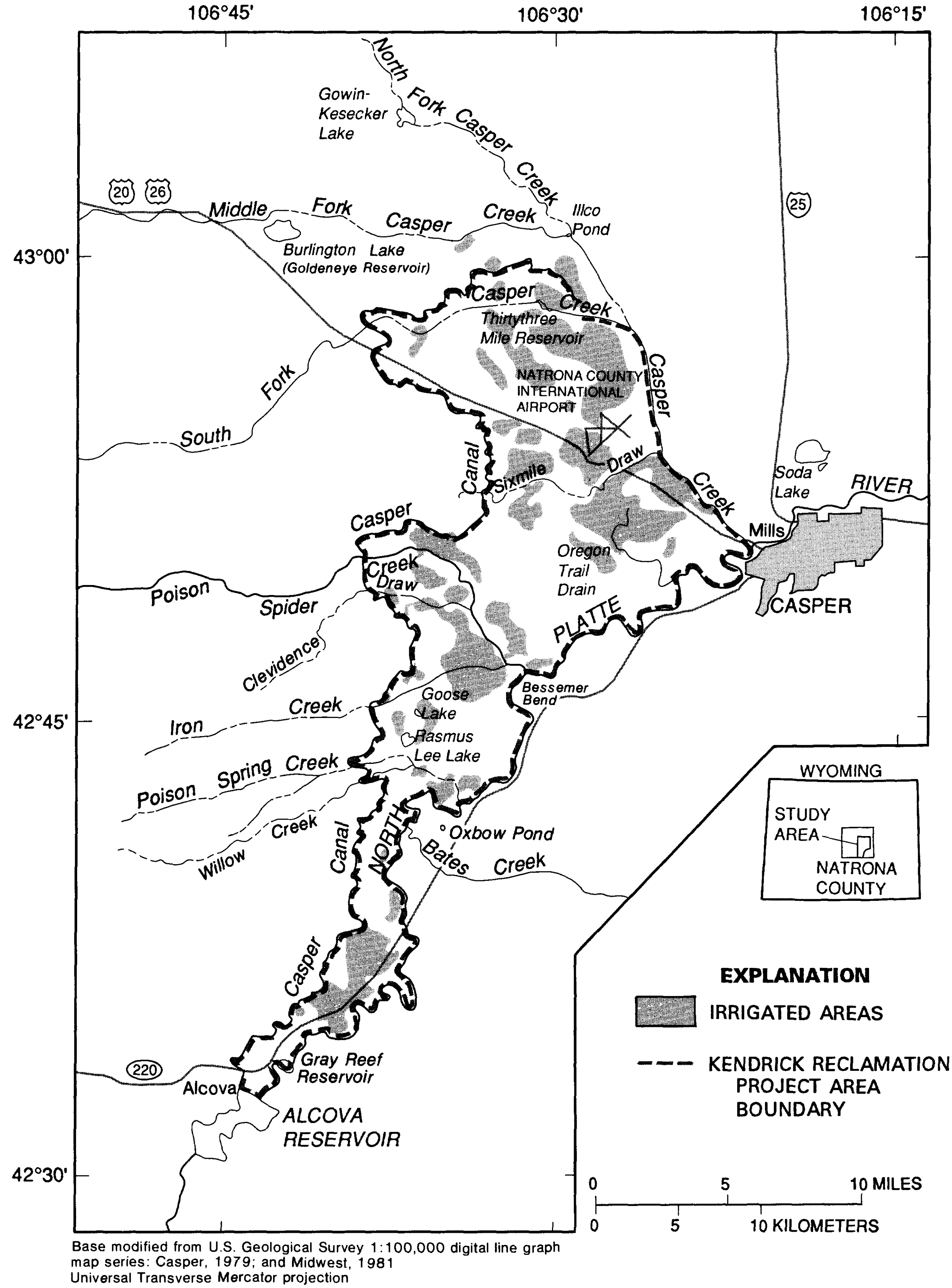

Figure 1.--Location of the study area and the Kendrick Reclamation Project area. (Irrigated areas modified from maps revised in 1982 by the Casper-Alcova Irrigation District.)

only about 24,000 acres (about 38 mi^2) are irrigated. Drainage from the Kendrick area is to the North Platte River. The drainage area of the North Platte River at Alcova Reservoir, at the upstream edge of the study area, is 10,800 mi^2.

A semiarid climate with average annual precipitation of about 12 in. prevails in the study area. For 1988, 6.6 in. of precipitation (about one-half of average) was recorded at the Casper weather station; pan evaporation totaled 61 in. at Pathfinder Dam about 9 mi southwest of the study area (National Oceanic and Atmospheric Administration, 1989, p. 20). The air temperature averaged 47.0 ^{0}F in 1988, which was 1.8 ^{0}F above average. The elevation of the Kendrick area ranges from about 5,000 to 6,000 ft above sea level. The topography is characterized by rolling hills vegetated with grasses and shrubs, including big sagebrush.

Prior to development of the irrigation plan for the Kendrick area, 90 percent of the land holdings were between 500 to 1,000 acres; most of the land was 640-acre homesteads. Much of the land was used as free range by adjoining ranches because many of the holdings were in small, unproductive, unfenced, and unleased tracts of land owned by nonresidents.

In 1869, Professor Cyrus Thomas visited the area, which is now the Kendrick area, and discussed the possibility of constructing an irrigation system (Hayden, 1872). Engineering, economic, and soil studies for the Kendrick area were completed in 1930 under an agreement between the Bureau of Reclamation and the State of Wyoming. Originally, the irrigation of 66,000 acres of land was planned. The Kendrick area was authorized as part of the National Industrial Recovery Act of 1933 and construction began that year. By 1939, 63 mi of main canal and 150 mi of lateral canals and ditches were completed. A total of 42 mi of unlined drains had been completed in the Kendrick area. Irrigation water was first made available in the Kendrick area in 1946. Irrigated area increased from 1,046 acres in 1946 to about 24,000 acres in 1989. The changes in the area of irrigated land and volume of water diversions in the Kendrick area are shown in figure 2. A chronology of selected events during the development and operation of the Kendrick area is shown in table 1.

The boundary of the Kendrick area corresponds to the boundary of the Casper-Alcova Irrigation District. Forage crops are the most important crops in the Kendrick area and are used primarily for stock-raising. About 20,000 of 24,000 irrigable acres are harvested annually. Alfalfa hay is grown on 55 percent of the irrigated land. The rest of the land is used as follows: (1) Other hay, irrigated pasture, and corn for silage--35 percent; (2) cereal crops such as corn and oats--5 percent; and (3) miscellaneous uses--5 percent (Peterson and others, 1988, p. 4). The high elevation and short growing season make it difficult to grow alternative crops. There are 102 full-time farms and 150 part-time farms in the area, with a resident population of 529 (Peterson and others, 1988, p. 4).

The North Platte River and the alluvium along the river are the sources of water for many domestic and industrial supplies, as well as for municipal water supplies for Casper and adjacent communities. Much of the ground water in the Kendrick area is too mineralized for domestic use. As a result, many of the farmers and ranchers transport drinking water from Casper. Livestock drink water from most of the creeks in the area, and in many places this is the only water available for them.

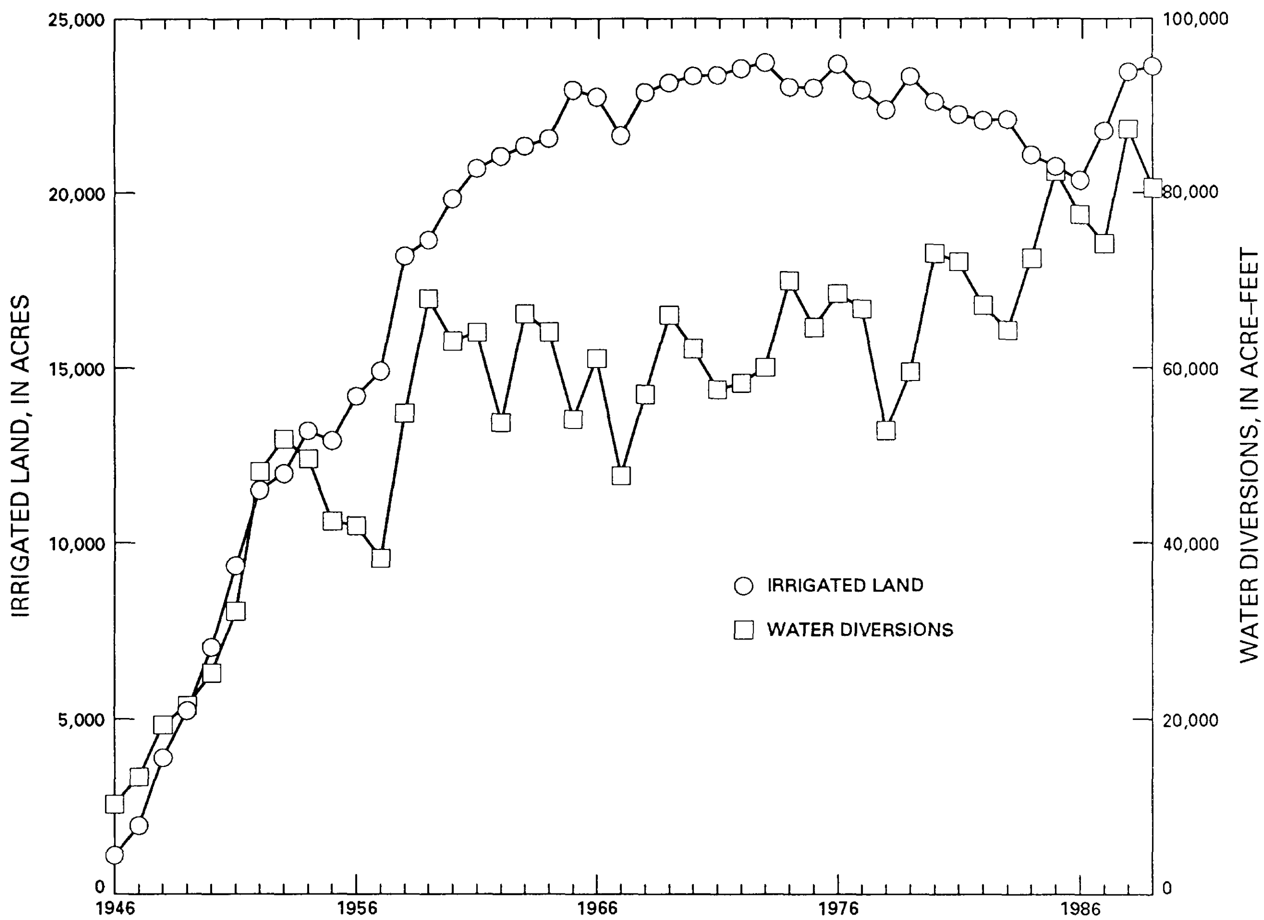

Figure 2.--Changes in area of irrigated land and volume of water diversion in the Kendrick Reclamation Project area, 1946-89. Data from John H. Lawson, Bureau of Reclamation, written communication (1990).

Table 1.--A chronology of selected events during construction and operation of the Kendrick Reclamation Project, 1930-91

Date	Activity
1930	Engineering, economic, and soil studies completed.
1933	National Industrial Recovery Act authorized construction and construction began.
1946	Water deliveries began, 1,046 acres were irrigated.
1950	6,981 acres were irrigated.
1960	19,759 acres were irrigated.
1970	23,254 acres were irrigated.
1972	Report published: Ground-water resources of Natrona County, Wyoming (Crist and Lowry, 1972)
1974	Report published: Selenium in waters in and adjacent to the Kendrick Project, Natrona County, Wyoming (Crist, 1974)
1980	22,531 acres were irrigated.
1983	Biologists concluded large selenium concentrations contributed to dead and deformed bird embryos at Kesterson Reservoir, California.
1985	National Irrigation Water Quality Program was established to review systematically areas in the western United States where irrigation-induced water-quality problems were present or could arise.
1987	Report published: Reconnaissance investigation of water quality, bottom sediment and biota associated with irrigation drainage in the Kendrick Reclamation Project (Peterson and others, 1988).
1992	Report published (this report): Detailed study of selenium in soil, representative plants, water, bottom sediment, and biota in the Kendrick Reclamation Project Area, Wyoming, 1988-90.

The Kendrick area includes several wetlands which provide habitat for aquatic birds and other wildlife. Wetlands are lowland areas that are saturated with water and range from marshes to open water. Wetlands are important resources to a large number of migratory birds, including waterfowl, shorebirds, waders, and other birds.

Soil in the study area is derived principally from Cretaceous formations of marine origin. The following description is based on a geohydrologic map of the area in the report by Crist (1974) and is from Peterson and others (1988, p. 6). The predominant formation is Cody Shale, with smaller outcrops of the underlying Frontier Formation and Mowry and Thermopolis Shales, the overlying Mesaverde Formation and the partly equivalent Niobrara Formation, and Steele Shale. The Cody Shale contains gray soft shale and lenticular sandstone beds; gray limey shale is present at the base of the Cody Shale. The other Cretaceous formations also include gray and black limey and carbonaceous shale beds, sandstone beds, thin coal beds, and bentonite beds. Several of the Cretaceous formations present in the Kendrick area have been described as seleniferous by Rosenfeld and Beath (1964, p. 23). Quaternary alluvium exists along the larger streams and in the northern part of the area, near the Natrona County International Airport.

The water supply for the Kendrick area is stored in two reservoirs on the North Platte River: Seminoe Reservoir, 70 mi southwest of Casper, and Alcova Reservoir, 30 mi southwest of Casper. Water is delivered from Alcova Reservoir to the Casper Canal on demand. The average annual volume of water diverted from the reservoir to the canal is 3.05 acre-ft per irrigated acre. The volume of water delivered to the land via the canal and lateral system ranges from 1.75 to 2.58 acre-ft per acre per year. Irrigation water in the project area is supplied primarily by the Casper Canal; a small quantity of irrigation water is obtained from ground-water or streamflow diversions from creeks in the Kendrick area.

About 43 mi of both open and closed drains in the Kendrick area include the Kramer, Townsend, Middaugh, Townsend Branch, Middle Branch, Bergesson Branch, Oregon Trail, Miller, Lovelace Meyer, Johnson-Dye, Garbutt, Johnson Reservoir, Sheppard, and Radden Drains. The wastewater from the Kendrick area flows through these drains as well as through streams tributary to the North Platte River. Wastewater is water transported in the canals and laterals but not used for irrigation. Wastewater ranges from 2,000 to 8,000 acre-ft per year. Drainwater is water that is applied to fields and either runs off or seeps into drains from subsurface flow.

Previous Studies

Prior to this investigation, several reports had documented the occurrence and distribution of selenium in surface water, ground water, sediment, or biota in the Kendrick area. Other reports have described the water resources, geology, and climate of the study area.

Reports by Larsen (1951) and Wilson (1951) described the geology and ground-water resources in different parts of the Kendrick area. Whitcomb and Lowry (1968) made a reconnaissance of the ground-water resources and of the geology of the Wind River basin; their study area included the southwestern part of the study area in this report. Crist and Lowry (1972) made a reconnaissance study of the ground-water resources of Natrona County. Water analyses in that report indicated that some ground water in the Kendrick area contained as much as 1,000 μg/L of selenium. Crist (1974) detected selenium concentrations exceeding 10 μg/L in surface-water samples collected in and adjacent to the Kendrick area and also detected variable selenium concentrations in water samples from some wells. These data indicate that selenium concentrations in some areas had not reached equilibrium conditions. DeBruin (1980) summarized the sources and quality of ground water in the study area.

The U.S. Soil Conservation Service (1983) identified and quantified seepage losses from the irrigation-water distribution system as part of an agreement to transfer 7,000 acre-ft of water from the Casper-Alcova Irrigation District to the city of Casper. A statistical summary of chemical constituents and characteristics of the water in the North Platte River between Alcova Dam and Orin, Wyoming was completed by Larson (1985).

Peterson and others (1988) conducted a reconnaissance investigation in the Kendrick area to determine if irrigation drainage caused or had the potential to cause harmful effects on water resources. Concentrations of dissolved selenium in the North Platte River ranged from less than 1 to 4 μg/L. Discharge of dissolved selenium increased in the downstream direction of the North Platte River. Bottom-sediment samples contained selenium concentrations ranging from 0.9 to 25 μg/g. Selenium concentrations in avocet livers (51-170 μg/g dry weight), mallard livers (43 and 56 μg/g dry weight), and eared-grebe eggs (14-20 μg/g dry weight) were at concentrations that could have toxic effects. Fish from some lake and pond sites had selenium concentrations (3.2-9.5 μg/g wet weight) exceeding the 2 μg/g level suggested by Baumann and May (1984) as sufficient to induce toxic effects.

Severson and others (1989a) and Erdman and others (1989) investigated selenium in soils and plants at the Kendrick area. Samples of soil derived from the Cody Shale tended to have larger selenium concentrations than samples of soil derived from other geologic formations, but large variation in selenium concentrations was detected in samples of soil in each formation. Samples of big sagebrush (<u>Artemisia tridentata</u> Nutt.) had a geometric mean concentration of 0.4 μg/g selenium, almost four times larger than the norm of 0.1 μg/g reported by Gough and Erdman (1983). The median selenium concentration in alfalfa samples was 0.9 μg/g. However, selenium concentrations in alfalfa samples from fields in 11 contiguous sections west of Natrona County Airport ranged from 4 to 40 μg/g, concentrations potentially hazardous to livestock when consumed for long periods of time. Severson and others (1989b) have listed geochemical data and assessed the variability of selenium concentrations in plant and soil samples from the Kendrick area. Severson and others (1987b) and Harms and others (1990) summarized chemical results for bottom material for irrigation drainage studies, including the Kendrick area.

Rich (1962) made a reconnaissance survey of the geology of the Hiland-Clarkson Hill area of Natrona County. Lageson (1980) prepared a geologic map of Natrona County, Wyoming. Bentonite deposits in the Rasmus Lee Lake area were mapped by Dengo (1946). Sims (1948) and Faulkner (1950) investigated the geology of the west end of Casper Mountain and the Bessemer Mountain-Oil Mountain area.

Environmental features of Natrona County, including surface water, climate, and precipitation have been summarized by DeBruin and Oliver (1980). A map prepared by Case and Boyd (1985) shows areas in the Kendrick area that have localized potential for large selenium concentrations in bedrock, soil, and vegetation. Plant specimens in the same area were reported by Rosenfeld and Beath (1964) to contain more than 500 $\mu g/g$ (reported as parts per million) selenium. Byers (1935) noted large concentrations of selenium in soil and plant materials from the Kendrick area.

Acknowledgments

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SOIL AND REPRESENTATIVE PLANTS

Two detailed geochemical surveys were conducted during the spring of 1988 to study and define the concentration, distribution, and variability of selenium in soil and representative plants of the study area. Big sagebrush is associated with nonirrigated soil and alfalfa is a major crop on irrigated soil in the study area. Big sagebrush and alfalfa were selected as representative plants because they are common in the study area and have been used in previous geobotanical mapping of areas of selenium deficiency and excess (Erdman and others, 1989, p. 4; Combs and Combs, 1986, p. 29). Alfalfa, a deep-rooted plant, seems to provide a good indirect measure of soluble selenium in the pore water at depth (Erdman and others, 1989, p. 23-25). In April 1988, native soil and big sagebrush (*Artemisia tridentata* Nutt.) were sampled throughout the nonirrigated, uncultivated rangeland. The native soil is referred to in this report as nonirrigated soil. This survey focused on soil overlying and developed from the specific geologic units of the study area as possible sources of the large selenium concentrations previously detected in bottom-sediment samples from the Kendrick area. In June 1988, irrigated soil and alfalfa (*Medicago sativa* L.) were sampled to evaluate concentrations of selenium for the irrigated land in the study area.

Sample Collection and Analytical Methods

The nonirrigated soil of the study area has developed on a variety of geologic units, including several Upper Cretaceous formations containing carbonaceous shale and thin coal beds (Niobrara Formation, Cody Shale, Mesaverde Formation, Meeteetse Formation, and Lance Formation) and several Tertiary formations containing bentonite, claystone, shale, and sandstone or siltstone (Fort Union, Wind River, and White River Formations). The units sampled are listed in table 2. Irrigated soil generally is limited to two geologic units: Quaternary alluvium and Upper Cretaceous Cody Shale. Separate sampling plans were designed for collecting samples of nonirrigated and irrigated soil. The nonirrigated soil was sampled to assess the source of selenium in the study area by using a stratified random and nested design. The irrigated soils were sampled on a grid system to allow mapping of the areal distribution of selenium concentrations.

A stratified and nested random sampling design was used to assess variation in selenium concentrations in samples of nonirrigated soil and big sagebrush among and within geologic units that occur in the study area. Figure 3 shows the generalized geology of the study area. Twelve townships were selected randomly for soil and plant sampling. For each of the geologic units occurring in each selected township, two locations were selected randomly for sampling. Fourteen geologic units (table 2) were identified for sampling in the twelve townships selected. Not all geologic units are present in each township. A total of 120 sites was sampled. The actual sampling was done at pre-selected sites where they were accessible, and as close as possible where accessibility was limited. The location of sampling sites and the townships sampled are shown in figure 4.

Table 2.--Geologic units from which soil was sampled in study area

System	Geologic unit	Number of samples
Quaternary	Alluvium	18
	Windblown sand	10
Tertiary	White River Formation (upper part)	2
	White River Formation (lower part)	6
	Wind River Formation	10
	Fort Union Formation	7
Cretaceous	Lance Formation	6
	Fox Hills Sandstone	2
	Mesaverde Formation	11
	Cody Shale	16
	Steele Shale	2
	Frontier Formation	12
	Mowry and Thermopolis Shales	8

At each site, a 3.5-in. bucket auger was used to collect a nonirrigated soil sample from the surface to a depth of about 3 ft. The sample from the 3-ft zone was mixed onsite and a representative 1-kg sample retained. Where present, samples of big sagebrush also were collected at the soil-sampling sites. The previous year's growth (new growth had not yet emerged) was clipped from several shrubs within a radius of about 33 ft of the soil-sampling site.

The objective of irrigated-soil and alfalfa sampling was to collect samples from currently or previously irrigated fields on a grid-interval that would allow the preparation of geochemical maps showing the spatial distribution of concentrations of selenium in these samples. Selection of the most efficient sampling plan and optimum grid size depend on knowledge of the spatial variability at increments of distance on the landscape for the sampling media and the trace elements of interest. Because this information was not available for the Kendrick area, a grid size of 1 mi was selected, based on studies of spatial variability of trace elements in the Northern Great Plains (Severson and Tidball, 1979) and the San Joaquin Valley (Severson and others, 1987a). Only parts of any given section are irrigated, and the irrigated fields are not contiguous. The target-sampling population was irrigated fields of 40 or more acres in a section; 110 sections met this criterion.

In early June 1988, samples of irrigated soil were collected from 109 fields (access permission was not received for one of the sections) and of alfalfa from 105 fields where it was present. For each field, two sites about 330 ft apart were chosen for sampling. A 3.5-in. diameter bucket auger was used to collect an irrigated soil sample from the surface to a depth of about 3 ft at each site. At each of the two sites in a selected field, the 3-ft

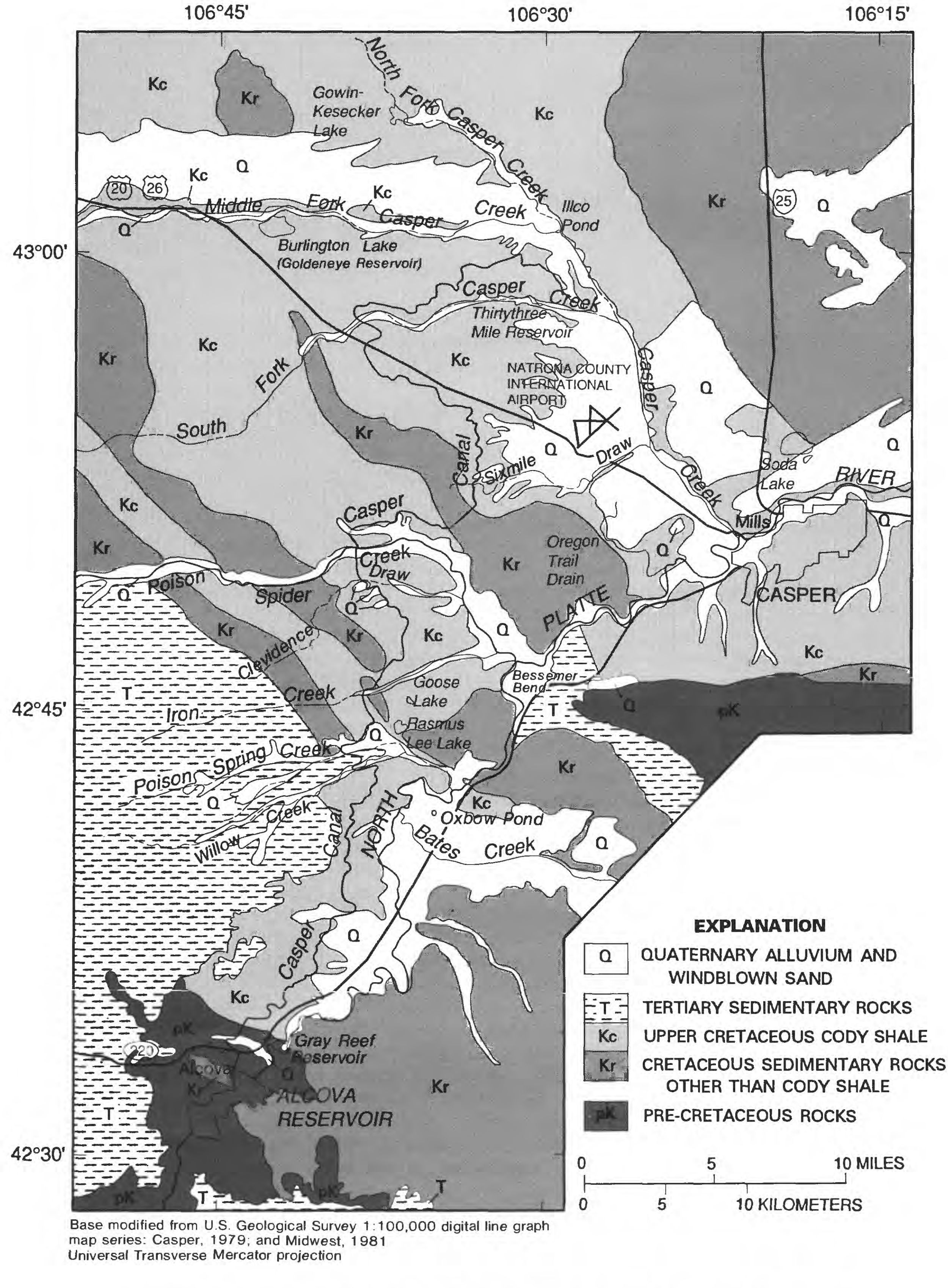


Figure 3.--Generalized surficial geology of the study area. (Modified from Crist, 1974, and Lageson, 1980.)

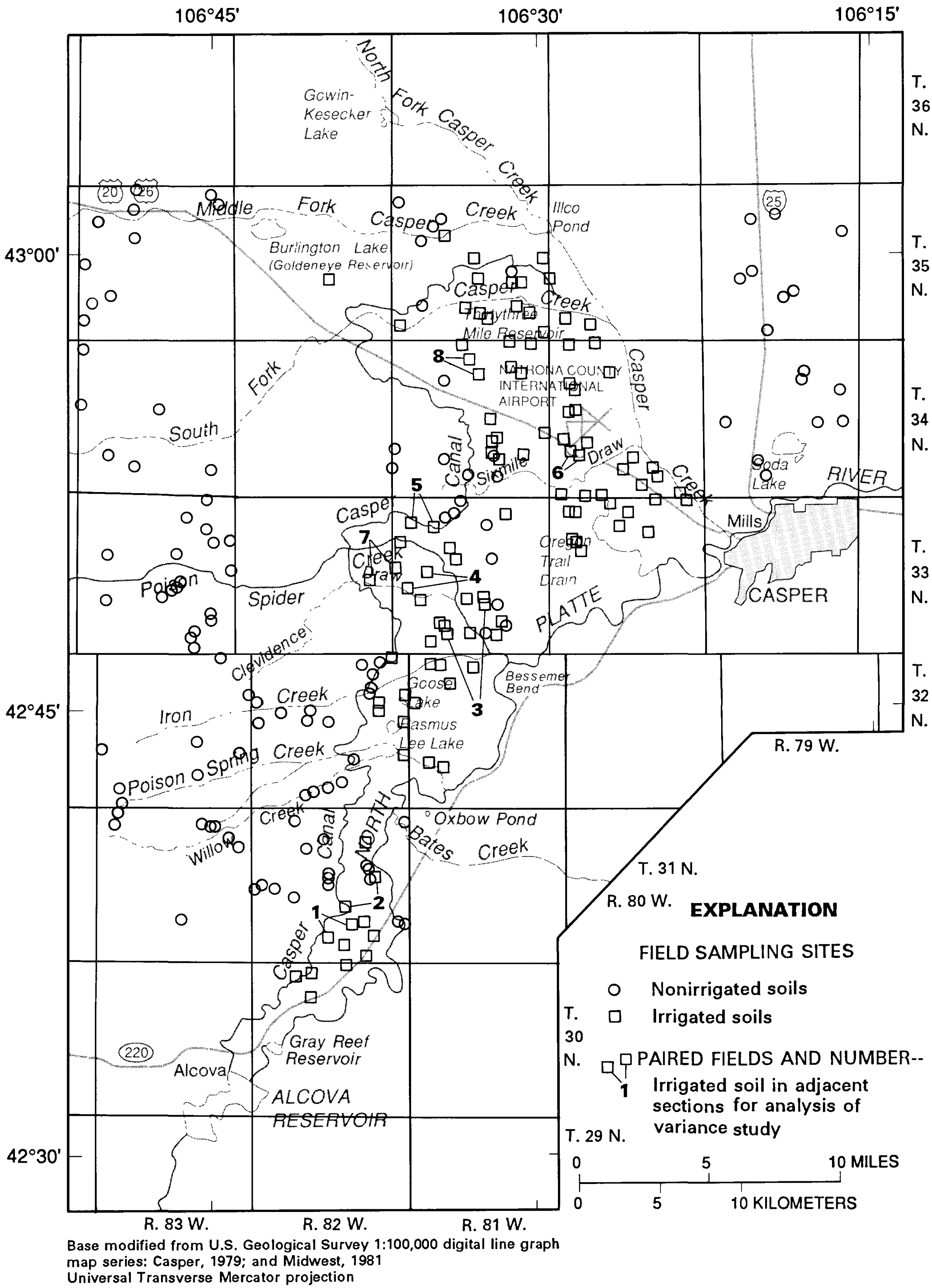


Figure 4.--Location of fields in which nonirrigated and irrigated soils, big sagebrush, and alfafa were sampled, and the location of fields for the analysis-of-variance study of the soils.

irrigated-soil sample was mixed, and a 1-kg sample was collected. The two samples of soil from sites in a single field were composited in the laboratory after the soil was air-dried and disaggregated to less than 10 mesh. Each alfalfa sample consisted of several plants collected within a few meters of the soil-sampling sites. The pairs of alfalfa samples for each field were blended to make a single composite sample.

In addition, eight irrigated soil- and seven alfalfa-sampling fields were selected randomly, and the two irrigated-soil samples and the two alfalfa samples were collected in each field and were analyzed individually. This set of samples was used to estimate within-field variation. The composite samples of irrigated soil from each of the 109 fields, and composite samples of alfalfa from each of the 105 fields, were analyzed. The locations of the fields used for sampling the irrigated soils and alfalfa are shown in figure 4.

A subset of 96 additional irrigated soil samples was collected, according to an analysis-of-variance design (ANOVA), in each of eight randomly selected fields (fig. 4). This additional soil sampling was conducted to assess the depth and lateral variation of the total selenium concentrations in soil. For each of the eight paired, within-field sites, a field from an adjacent section was selected for additional soil sampling. In each of the eight fields where paired samples were collected, two irrigated-soil profiles were sampled at distances of about 330 ft apart. Samples of the A, B, and C soil horizons, where present, were collected and analyzed. Where distinct horizons were not present in a soil profile, the 0-8 in., the 8-24 in., and the 24-40 in. zones were sampled.

On June 6, 1989, hay was sampled by H. Mayland (U.S. Department of Agriculture, written commun., 1989) in two fields where alfalfa that was sampled in 1988 contained 15 and 25 μg/g selenium. Both fields are underlain by Cretaceous Cody Shale. The hay contained about 85 percent alfalfa and 15 percent smooth bromegrass (<u>Bromus</u> <u>inermis</u> Leyss). Plants were in early bud stage (12 in. tall) and flower stage (14 in. tall). The first harvest of the season occurred 2 weeks after sampling. Selenium indicator plants in this area, such as grooved poison vetch (<u>Astragulus</u> <u>bisculcatus</u>) and woody aster (<u>Xylorrhiza</u> <u>glabriuscula</u> Nutt.), were in early bloom stage.

Two to four tillers (above 1.5 in. stubble height) each of alfalfa and smooth bromegrass were collected by Mayland from each of about 50 sites, grouped in four areas, at two fields. One of the areas sampled was a 40-acre field having 1.5 percent slope and an easterly aspect. Three remaining areas were parts of a 40-acre field containing 10 acres having 2 to 3 percent slope on a northerly aspect and an upper and lower site on the other 30 acres, having a 2 to 4 percent slope and a southeasterly aspect.

Grab samples of rocks, soils, and salt crust were collected at various locations throughout the study area on the basis of onsite observations of some unusual characteristic. Rock outcrop was sampled by taking a channel sample with a rock hammer. The sample was crushed to about 10 mesh in a mechanical jaw crusher, split, and ground to pass 80 mesh. This split and ground rock sample was analyzed by using the same method as used for soil samples. Grab-soil samples were collected from a depth of 0-6 in. and prepared and analyzed by using the same method used for other soil samples. Two grab samples of salt crust at the edge of Rasmus Lee Lake were collected and processed as soil.

All samples of soil, big sagebrush, alfalfa, rock, and salt crusts collected by USGS personnel were mailed to USGS laboratories in Denver, Colorado for preparation and analysis. The samples of soil, rock, or salt crust were dried under forced air at ambient temperatures. The dried samples were disaggregated with a mechanical mortar and pestle and the minus 10 mesh (2 mm) fraction sieved and saved for analyses. A split of the minus 2-mm fraction was ground in a ceramic plate grinder to minus 100 mesh, and this fraction was used for all chemical analyses. All plant samples were washed to remove possible surface contamination. The washed plant samples were dried at ambient temperature for 24 hours followed by a 15-minute finish cycle in a microwave oven. The dried plant samples were pulverized to less-than two millimeters in a Wiley mill.

Selenium concentration in soil samples was determined by continuous-flow, hydride generation atomic-absorption spectroscopy (HGAAS) (Crock and Lichte, 1982; Sanzolone and Chao, 1987). The relative standard deviation (RSD) for the determination of selenium concentration was about 10 percent and had a reporting limit of 0.1 μg/g.

Water-extractable selenium (WX-Se) was determined on a 1 to 5 (5 g soil to 25 ml demineralized water) soil-water extract. After shaking the extract for 4 hours, centrifuging at 2,500 revolutions per minute, and filtering through a 0.45 μm filter, a clear extract was obtained. Selenium concentration was determined by HGAAS using this clear solution.

Nonirrigated and irrigated soil samples from both geochemical surveys were selected at random to be split into two parts and analyzed separately to estimate errors associated with sample preparation and analysis. The samples from each survey, plus sample splits, were arranged in a random sequence and were prepared and analyzed in that sequence to convert any systematic errors in preparation and analysis to random errors and to estimate relative laboratory precision. Reference samples of USGS SCo-1 Cody Shale were inserted at random intervals into the sample sequence to estimate laboratory accuracy. Reported consensus values from the literature, when compared with USGS laboratory determinations, indicate that the soil selenium determinations were accurate (Severson and others, 1989b).

Selenium in samples of vegetation was determined fluorometrically after complexing with 2,3-diaminonapthlene and extracted into an organic solvent (Harms and Ward, 1975). The reporting limit was 0.01 μg/g with an RSD of 10-15 percent.

Several biological standard reference materials from the National Bureau of Standards were analyzed for selenium by the fluorometric method listed above. Gladney (1980) analyzed these same materials by neutron activation analysis. Close agreement between the certified values, the values determined by Gladney (1980), and the values determined by the USGS indicate that determinations of selenium in plant samples were accurate (Severson and others, 1989b).

Nonirrigated Soil and Big Sagebrush

Ranges of baseline concentration of total selenium in soils of the Northern Great Plains, as well as those for soils from three other regional studies in the West, are given in table 3. The sampling media for each of the

Table 3.--Ranges of baseline concentration of total selenium in soil samples from selected studies in the western United States

[Detection ratio, number of samples in which the element was detected in reportable concentrations to number of samples analyzed; GM, geometric mean; GD, geometric deviation; baseline range, expected 95-percent range; <, less than]

Reference and general location of the study area	Detection ratio	Concentration, in micrograms per gram			
		GM	GD	Observed range	Baseline range
Shacklette and Boerngen (1984) western half of the United States	590:733	0.23	2.43	<0.1-4.3	0.039-1.4
Severson and Tidball (1979) Northern Great Plains, parts of Montana, Wyoming, and North Dakota	104:136	.45	2.72	<0.1-20	0.061-3.3
McNeal (unpublished) San Joaquin Valley, California	240:328	.14	2.56	<0.1-2.8	0.021-.92
Severson, and others (1987a) Panoche Fan, San Joaquin Valley	713:721	.68	1.94	<0.1-4.5	0.1-2.2

studies in table 3 differ from one study to another and so are not exactly comparable. Samples from the western half of the United States (Shacklette and Boerngen, 1984) were collected from the B horizon and below 8 in. where the B horizon was undefined; surface or A-horizon samples were collected for the Northern Great Plains study (Severson and Tidball, 1979); and the surface 0-8 in. were collected for the San Joaquin Valley study (J.M. McNeal, U.S. Geological Survey, Reston, Va., written commun., 1989). Samples of soil from a depth of 66-72 in. were collected from the Panoche Fan, located on the west side of the San Joaquin Valley, California (Severson and others, 1987a). These ranges of baseline concentrations are valid for comparing analyses of the same kind of sample from the area where the baseline concentration was developed. They should be applied with caution to different sample media or to samples collected outside of the baseline area. They indicate ranges in total selenium concentrations determined for soil samples from different parts of the western United States. Additional data on selenium concentrations in soil samples collected worldwide are summarized by Berrow and Ure (1989).

All of the nonirrigated soil samples contained total selenium concentrations less than the 3.3 μg/g baseline established for soil samples from the Northern Great Plains (Severson and Tidball, 1979). The relative normalcy of the soil samples from the study area is surprising when compared to the large concentrations of selenium detected in the associated big sagebrush. A comparison of the ranges and geometric means for total selenium in soil samples collected from soil overlying various geologic units (fig. 5) shows that samples of soil overlying the Cody Shale (0.64 μg/g) and Mowry and Thermopolis Shales (0.47 μg/g) have a larger range of total selenium concentrations than those overlying the other geologic units and only the geometric-mean concentration of samples of soil overlying the Cody Shale exceeds that for soil samples from the Northern Great Plains.

An F-test shows statistically significant differences (significance level = 0.05) in total selenium concentrations in samples of the nonirrigated soil among geologic units and between locations within townships. This result suggests that geologic units play an important role as a source of selenium, but soil overlying a specific unit, such as the Cody Shale, is not uniformly seleniferous. In fact, the small-scale variation that occurs between sites from randomly selected locations within townships exceeds that between geologic units. Results of the analysis-of-variance for the nonirrigated soils, expressed as a percentage of the total variance, are given in Severson and others (1989b, table 6).

In the study area, the geometric-mean concentration of selenium in samples of big sagebrush is 0.41 μg/g--four times higher than the norm of 0.11 reported by Gough and Erdman (1983) for big sagebrush from the western United States. The concentrations of selenium in samples of big sagebrush from the study area range from 0.06 to 9.5 μg/g (fig. 6). Concentrations of selenium in 13 samples exceeded the 1.1 μg/g upper baseline range (Gough and Erdman, 1983) determined for the western United States. The four outliers--9.5, 7.5, 6.5, and 5.5 μg/g--came from sites underlain by Cody Shale. The results indicate that big sagebrush growing on the Cody Shale typically contains selenium concentrations approaching or exceeding the upper concentration of the baseline range.

The concentrations of selenium in big sagebrush from the study area are not extreme when compared to selenium in big sagebrush from the nearby Powder River basin. In a reconnaissance study of the Powder River basin of Wyoming and Montana, Connor and others (1976) reported a geometric-mean concentration of 0.43 μg/g selenium and an observed range of 0.08 to 4.8 μg/g for samples of big sagebrush from 41 localities, similar to that for big sagebrush from the study area.

Like the native soil results, the most seleniferous big sagebrush comes from areas underlain by Cody Shale. In contrast to the native soil results, many of the big sagebrush samples contained large levels of selenium when compared to norms. Yet some of the big sagebrush sampled from the Cody Shale contained the smallest concentrations. Some big sagebrush samples from five other geological units, including alluvium deposits of Quaternary age, also had selenium concentrations that exceeded the established upper baseline of 1.1 μg/g for the western United States. However, most big sagebrush with small selenium concentrations tended to grow at sites mapped as Quaternary alluvium or windblown-sand deposits.

Analogous to the results given for the native soil, significant differences can be attributed to geology, but by far the largest variation for selenium in big sagebrush occurred between sites on a single geologic unit, with the largest disparities from sites on the Cody Shale. Results of the analysis-of-variance for the big sagebrush, expressed as a percentage of the total variance, are given in Severson and others (1989b, table 8).

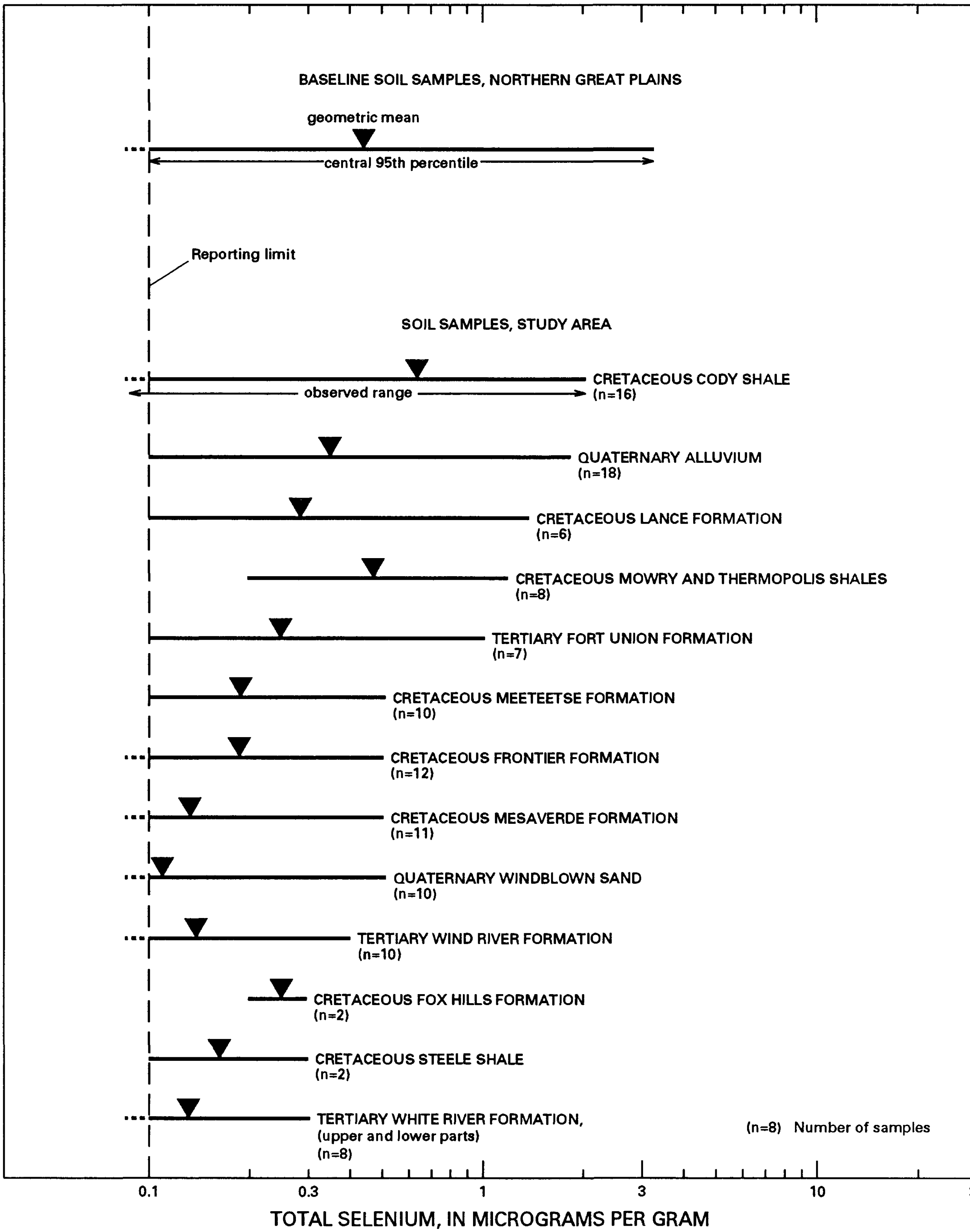


Figure 5.--Concentrations of total selenium in samples of nonirrigated soil overlying various geologic units, arranged in order of decreasing maximum concentrations. Dashes indicate that the minimum concentration of the observed range was less than the 0.1 μg/g analytical reporting limit. (Baseline data from Severson and Tidball, 1979.)

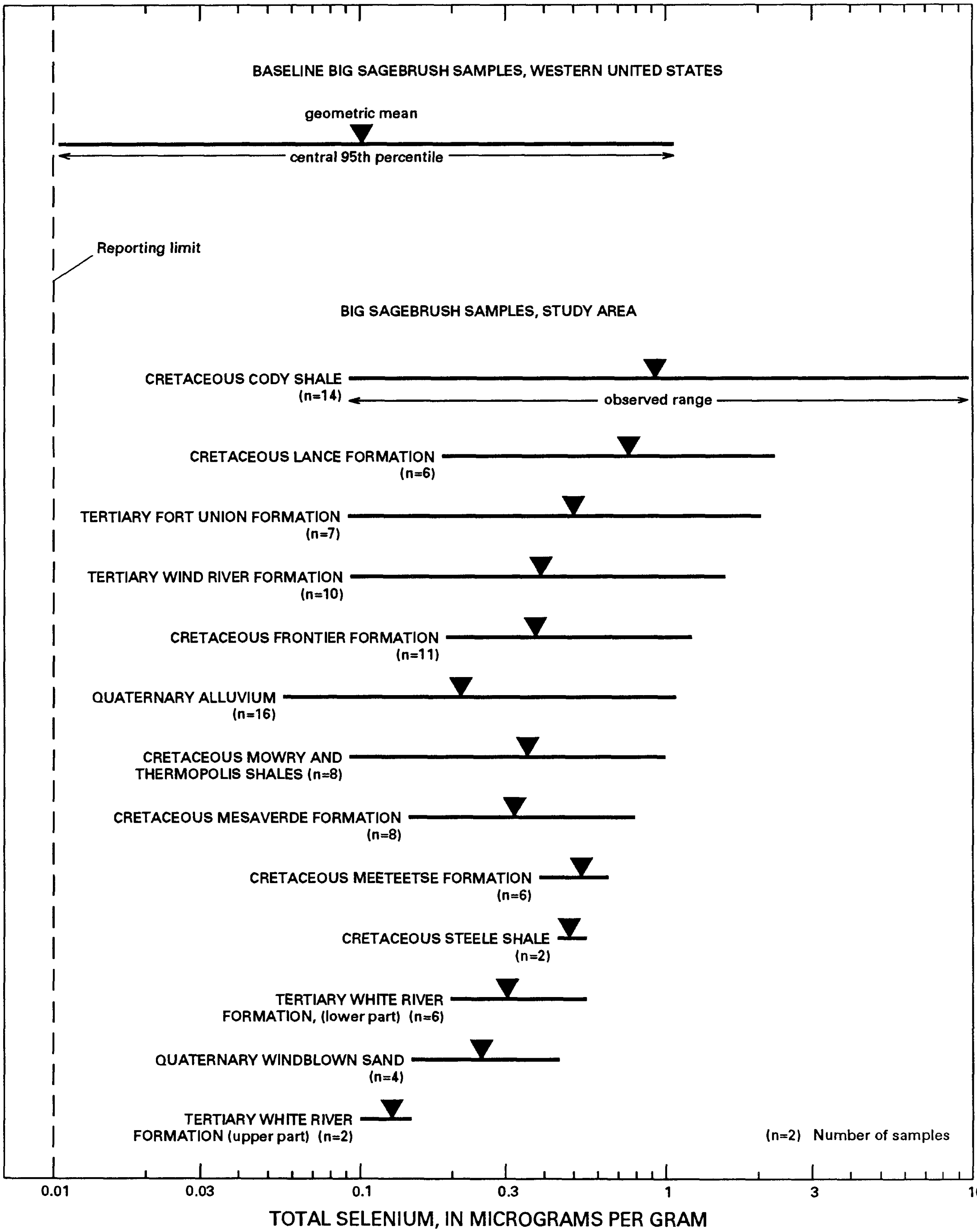


Figure 6.--Concentrations of total selenium in samples of big sagebrush from geologic units, arranged in order of decreasing maximum concentrations. (Baseline data from Gough and Erdmann, 1983.)

The Cody Shale appears to be the most seleniferous of the geologic units in the study area, especially in terms of availability, as indicated by the concentrations of selenium in big sagebrush; but it is not uniformly so. The four most selenium-rich big sagebrush samples were taken from sites that were not close to each other. This prevents narrowing the source of selenium in the uncultivated native soil to a specific area.

A low, but significant (significance level = 0.05) correlation ($r = 0.34$, $n = 101$ pairs) was found for total selenium in soil in relation to big sagebrush. Such poor correlations have been widely reported in the literature. Olson and others (1942) even found a poor correlation between water-soluble selenium in the surface soil and the selenium concentration of plants growing in the soil. Still, three of the four sites where big sagebrush contained the largest selenium concentrations also had soil with large selenium concentrations. Summary statistics for selenium in the native soil and big sagebrush from the various geologic units are given in table 4.

Table 4.--Geometric mean and observed range of total selenium concentrations in samples of nonirrigated soil and big sagebrush determined from stratified random sampling of geologic units

[Analytical duplicates not included. Detection ratio, number of samples in which the element was detected in measurable concentrations relative to the number of samples analyzed; geometric mean and observed range, total selenium concentrations, in micrograms per gram dry weight]

Geologic unit	Nonirrigated soil			Big sagebrush		
	Detection ratio	Geometric mean	Observed range	Detection ratio	Geometric mean	Observed range
Alluvium	18:18	0.35	0.1-1.9	16:16	0.22	0.06-1.2
Windblown sand	7:10	.11	<.1- .5	4:4	0.25	.15-0.45
White River Formation (upper and lower parts)	7:8	.14	<.1- .3	8:8	0.24	.1 -0.55
Wind River Formation	8:10	.14	<.1- .4	10:10	0.41	.1 -2.0
Fort Union Formation	7:7	.25	.1-1.0	7:7	0.52	.1 -2.2
Lance Formation	6:6	.28	.1-1.4	6:6	0.79	.2 -2.2
Fox Hills Sandstone	2:2	.24	.2- .3	1:1	.3	.3 - .3
Meeteetse Formation	10:10	.19	<.1- .5	6:6	.53	.4 - .65
Mesaverde Formation	10:11	.13	<.1- .5	8:8	.32	.15- .8
Cody Shale	15:16	.64	<.1-2.1	14:14	.96	.1 -9.5
Steele Shale	2:2	.17	.1- .3	2:2	.5	.45-.55
Frontier Formation	11:12	.19	<.1- .5	11:11	.39	.2 -1.6
Mowry and Thermopolis Shales	8:8	.47	.2-1.2	8:8	.36	.1 -1.0

Irrigated Soil and Alfalfa

The ANOVA design for defining lateral and vertical variation consisted of a nested plus crossed classification (Bennett and Franklin, 1967). Two irrigated soil profiles spaced 100-m apart were sampled from fields in two adjacent sections in each of the eight randomly selected locations. At each profile, three depth zones (0-8, 8-24, and 24-40 in.) or horizons (where present) were sampled. This sampling design and the ANOVA results of this design expressed as variance components for main effects and their interactions are summarized in Severson and others (1989a, table 1).

The concentration of total selenium in samples from the soil profiles varied little (only 0.4 percent) between depth zones. Therefore, a single map showing distribution of selenium concentrations prepared using the data from any one depth zone, or a composite sample of all depth zones as was collected for the gridded sampling, should represent soil-composition patterns for all depth zones reliably.

The profile, section, and location variance components represent the nested portion of the ANOVA design. These components estimate variation over increments of lateral distance. The distance between profiles is about 330 ft, between sections is from 0.5 to 2.0 mi, and between locations is from about 2.0 to 24 mi. The concentration of total selenium varies significantly (significance level = 0.05) between locations and sections. This suggests that map patterns showing selenium distribution can be prepared by choosing a sampling interval based on the resolution necessary to meet the objectives of the investigation. However, the stability of the map depends on the variance of selenium with distance. About 65 percent of the total variation of selenium occurs between locations, and nearly 75 percent of its total variation occurs between locations plus sections. There was not a significant difference (significance level = 0.05) for the two profiles at a given sampling site. A map prepared for selenium based on a sampling interval of about 12 mi would show the gross distribution of selenium on the irrigated landscape, and a two-mi or less sampling grid would reproduce the detail of the irrigated landscape with greater resolution.

The geometric means and geometric deviations for the zones of irrigated soil are shown in table 5. The concentrations among zones are not significantly different. When compared to the literature values for selenium in the Northern Great Plains (Severson and Tidball, 1979), summary statistics for the soil in the study area are not anomalous.

Differences in total selenium concentrations in soil among irrigated fields are significant and account for 75 percent of the variance of selenium concentrations in soil. The range of total selenium concentrations in soil samples is shown in figure 7. The distribution of variance, expressed as a percentage of the total variance, is shown in Severson and others (1989b, table 4). Only a small percentage of the variance observed can be attributed to analytical error.

Four areas (seven sites) had total soil selenium concentrations exceeding 2 $\mu g/g$: the southernmost field in the irrigated area (selenium concentration, 2.2 $\mu g/g$); Rasmus Lee Lake (a single-point anomaly of 3.6 $\mu g/g$); Oregon Trail Drain, west of the junction of Casper Creek with the North Platte River (a single-point anomaly of 3.8 $\mu g/g$--the maximum measured); and northwest of the Natrona County Airport (a four-point anomaly with values ranging from 2.2-3.2

Table 5.--Summary statistics for total selenium concentrations in irrigated soil samples from analysis-of-variance and gridded irrigated field sampling sites and data for the Northern Great Plains

[GM, geometric mean; GD, geometric deviation]

Total selenium concentration, in micrograms per gram dry weight									
Kendrick Reclamation Project area								Northern Great Plains[1]	
Analysis-of-variance locations						Field locations			
Surface zone		Mid zone		Lower zone		3-foot composite		A horizon	
GM	GD	GM	GD	GM	GD	GM	GD	GM	GD
0.32	2.29	0.37	3.02	0.40	2.99	0.37	2.85	0.45	2.72

[1]Data from Severson and Tidball, 1979.

μg/g). A threshold concentration of 2 μg/g was used because soils in North America that are associated with selenosis usually contain 2-6 μg/g or more of total selenium (Thornton, 1981, p. 14). Composited soil samples from only seven of the irrigated fields sampled contained selenium in excess of the 2 μg/g threshold. As with the results from the nonirrigated soils in the project area, the concentrations of selenium from the irrigated soil probably would not prompt much interest when compared with the baselines reported for the Northern Great Plains (table 5). However, concentrations of total selenium in soil may not reflect directly irrigation-induced effects such as increased solubility, transport, and accumulation by irrigation drainage, nor would it reflect selenium uptake by native and agricultural plants and subsequent consumption by wildlife and livestock.

Selenium concentrations in samples of alfalfa ranged from 0.1 to 40 μg/g; the median was 0.9 μg/g, the 25th percentile was 0.4 μg/g and the 75th percentile was 2.0 μg/g. Large concentrations of selenium in alfalfa (>2.0 μg/g) were found in three of the four areas identified by the irrigated soil results: Rasmus Lee Lake; Oregon Trail Drain, west of the junction of Casper Creek; and an extensive area underlain by Cody Shale west of the airport (fig. 3) offset slightly to the south of the seleniferous (2.2-3.2 μg/g) soil area. The distribution of the concentration of total selenium in samples of alfalfa growing in irrigated soil is shown in figure 8. The extensive area consists of 11 contiguous sections west of the Natrona County Airport where total selenium concentrations in alfalfa samples ranged from 4 to 40 μg/g, concentrations that are potentially hazardous to livestock when consumed for extended periods of time (Church and others, 1971, p. 506; Combs and Combs, 1986, p. 26; Kingsbury, 1964, p. 47; and Lakin, 1973, p. 96). According to Church and others (1971), alkali disease (manifested by loss of hair and sloughing of hooves) is caused by consuming hay and grass with total selenium concentrations ranging from 10 to 30 μg/g. However, reported incidences of selenosis are not common in the study area. Although anecdotal accounts of selenosis exist, no occurrences of selenosis have been documented in the study area.

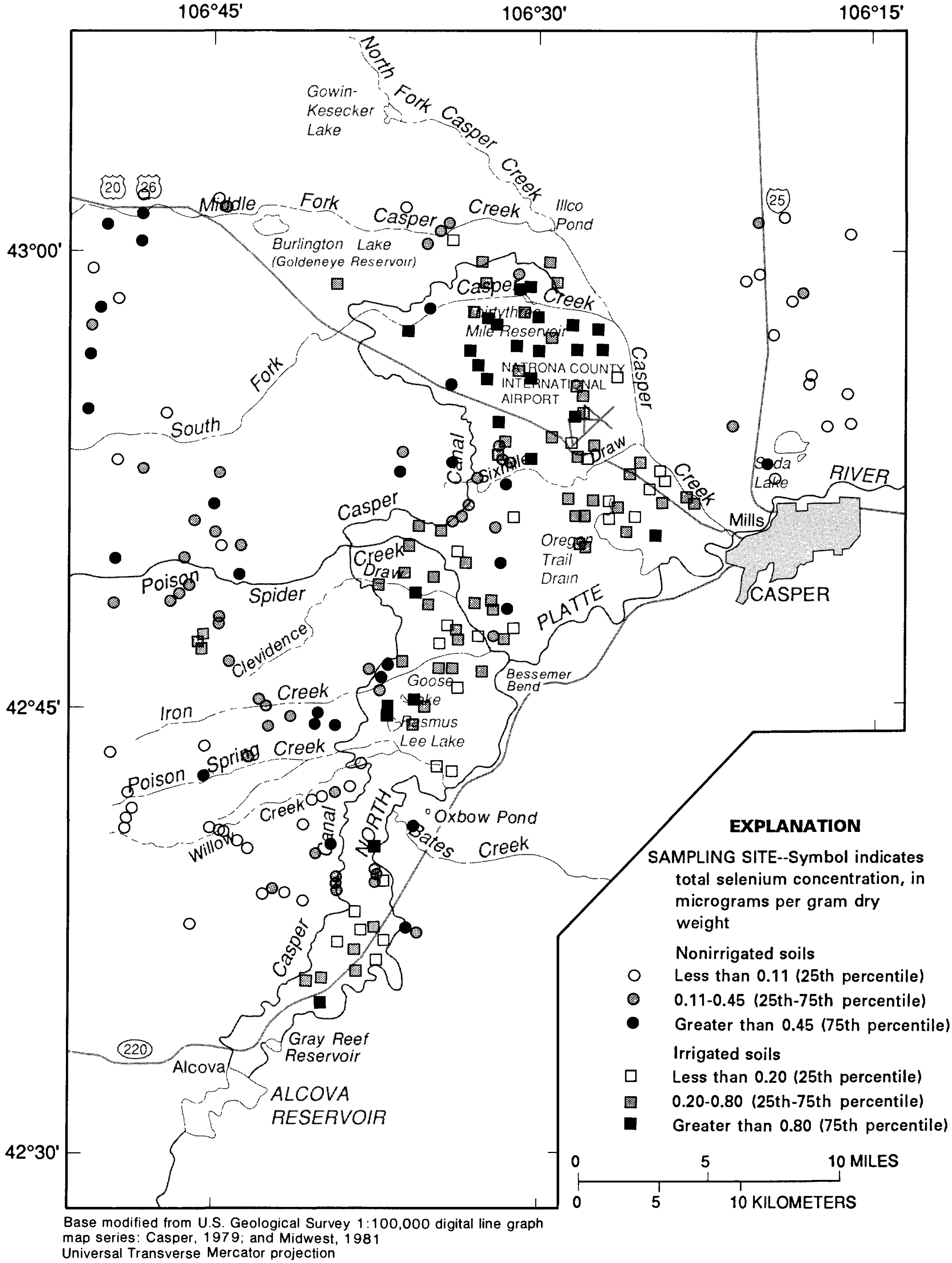


Figure 7.--Location of sampling sites and range of total selenium concentrations in composited soil samples.

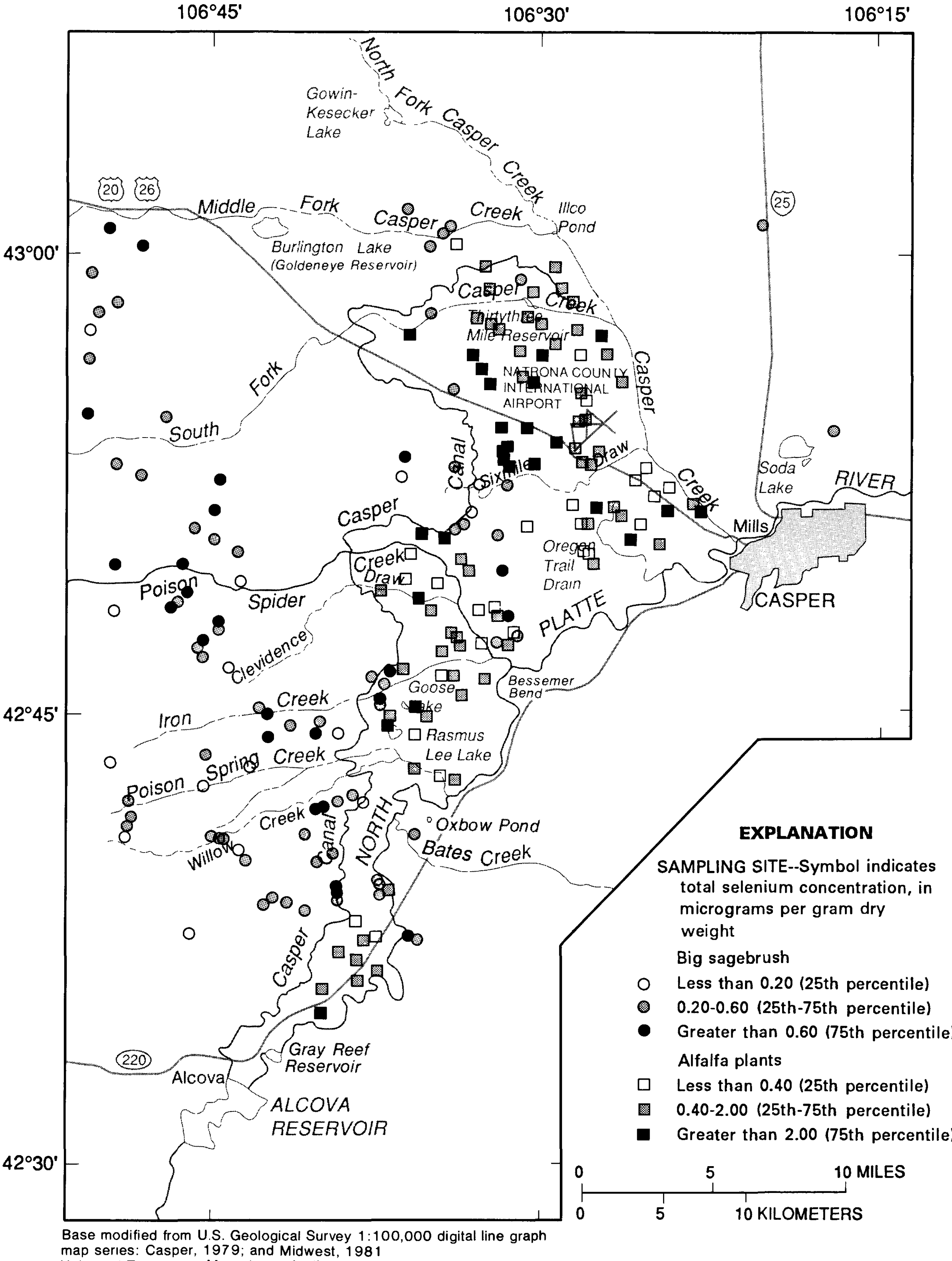


Figure 8.--Distribution of total selenium in big sagebrush and alfalfa samples.

Fifteen percent of the alfalfa sampled in the irrigated fields contained concentrations of total selenium exceeding 4 $\mu g/g$. It is difficult to assess the importance of the large values because most published studies on selenium in alfalfa are from selenium-deficient or nonseleniferous regions (Ihnat and Wolf, 1989). Several exceptions include an early study by Byers and others (1938) that reports a maximum concentration of 7 $\mu g/g$ selenium in alfalfa from southeastern Colorado. A second exception is a reported maximum concentration of 44 $\mu g/g$ selenium in alfalfa grown in Israel (Ravikovitch and Margolin, 1957). There is a record (O. Olson, South Dakota State University, written commun., 1975) of an alfalfa sample that contained 27 $\mu g/g$ selenium (no record of sampling location is available). Concentrations of 12 and 13 $\mu g/g$ were detected in two samples of alfalfa collected from Wallace Meadows northeast of Lusk, Wyoming (H. Mayland, U.S. Department of Agriculture, written commun., 1989). In contrast, selenium concentrations in alfalfa from eight fields in the Kendrick area were low (0.10-0.20 $\mu g/g$). According to Allaway and Hodgson (1964), Fisher and others (1987), and Westermann and Robbins (1974), a minimal dietary selenium concentration--critical concentration needed to prevent white muscle disease (a form of muscular dystrophy) in livestock--is about 0.1 $\mu g/g$. Alfalfa that contained selenium concentrations less than 0.5 $\mu g/g$ generally came from fields in the southern half of the Kendrick area.

Results of the ANOVA show that differences in total selenium concentrations in soil samples among fields are the main source of variance in total selenium concentrations in alfalfa samples. This is similar to soil results. The distribution of the variance of total selenium concentrations in alfalfa samples is shown in Severson and others (1989b, table 5).

Results from the Rasmus Lee Lake area provide an example of the extreme differences observed among fields. The composite alfalfa sample from an irrigated pasture used for grazing just northwest of the lake contained 15 $\mu g/g$ total selenium, whereas a sample from a heavily irrigated hay field to the east contained only 0.25 $\mu g/g$.

Unlike the results for total selenium in the irrigated soil samples, there were large differences in total selenium concentrations in alfalfa samples collected in the same field. The largest difference occurred between two sites from a field where the sample from the first site contained a total selenium concentration of 0.85 $\mu g/g$, and the sample from the second site contained 7.0 $\mu g/g$. These results are similar to those reported by Olson and others (1942) who also determined large variations in the total selenium concentrations in plants short distances apart on soil derived from the same parent material. Where such comparisons could be made, differences between site pairs from the other six fields were less extreme.

Results of a correlation analysis that compared total selenium concentrations in the irrigated soil samples with total selenium concentrations in alfalfa samples from the same fields were similar to the correlation between nonirrigated soil and big sagebrush. The correlation coefficient in this case was 0.43 ($n = 105$ pairs). Although the correlation is significant (significance level = 0.05), it explains only about 16 percent of the variation between total selenium concentrations in soil and alfalfa samples.

The offset or displacement of a large zone of seleniferous alfalfa (greater than 2.0 $\mu g/g$) from a possible source area of slightly seleniferous soil (as much as 3.2 $\mu g/g$) to the north is difficult to explain. Tidball and others (1989) reported what appears to be a very similar situation in an irrigated area of the San Joaquin Valley, California. Large concentrations of selenium in soil have been displaced downslope toward areas where the water table is close to the surface and where the ground water is extremely seleniferous.

To help explain the displacement in the alfalfa with large total selenium concentrations, water-extractable selenium concentrations were determined. A map of the sampling sites and range of water-extractable selenium concentrations in soil samples is shown in figure 9. The largest concentration corresponds to an area of ground-water depression southwest of the Natrona County Airport (Crist, 1974) and to the larger total selenium concentrations in the alfalfa samples. Correlations of total selenium concentrations in soil samples, water-extractable selenium concentrations in soil samples, and total selenium concentrations in plant samples are presented in table 6. The cause for this displacement of a large zone of seleniferous alfalfa from a possible source area of slightly seleniferous soil might be because of ground-water flow patterns in this area. Evaporation in the area of ground-water depression could explain the large selenium concentrations in the zone.

The correlation between water-extractable selenium in soil samples and total selenium concentration in plant samples is better than between total selenium concentrations in soil samples and selenium concentrations in plants. Because the soil of the Kendrick area generally contains little organic material, has alkaline pH values, and is oxidized, selenium should be present predominantly as Se(VI) selenate species. Because selenate is soluble and not readily adsorbed by soil materials, it should be mobile and available to plants. This is shown by the larger correlation coefficients of water-extractable selenium in soil samples and selenium concentrations in plants.

The selenium concentrations in alfalfa samples collected from two seleniferous fields in June 1989 were less than 5 percent of the concentrations detected in alfalfa samples from the same fields in June 1988. In the field where the 1988 sample contained a selenium concentration of 25 $\mu g/g$, the three 1989 samples contained only 0.2 $\mu g/g$; and in the field where the 1988 sample contained 15 $\mu g/g$, the single 1989 composite sample had 0.7 $\mu g/g$. The analyses were verified by data obtained from six laboratory-reference alfalfa samples, two of which were from the 1988 sampling of these two fields.

The large temporal variation, measured at the two fields sampled in 1988 and again in 1989, was unexpected. Examination of weather patterns and management practices might explain the results. Discussions with the owners of both farms revealed that the fields were quite dry during the 1987-88 winter and were not irrigated until after the initial sampling in early June 1988. Irrigation-water management was then improved by installation of gated pipe on one farm and more timely and adequate irrigation on both farms. Fields were watered in late 1988 and twice again during the subsequent spring before the June 6, 1989, sampling. On one field, alfalfa hay yields were fair in 1988 and very good in 1989; the 1989 yields on the second field were expected to quadruple those of 1988 because of better water management.

Selenate selenium might have been concentrated in the minimal pore water in the soil profiles preceding the 1988 sampling and the selenate selenium was readily absorbed by the alfalfa plants. The relatively dry soil limited plant growth, and selenate was concentrated in the plant tissue collected in early June 1988. Subsequent irrigation in the late fall of 1988 and twice before sampling on June 6, 1989, might have leached the selenate below the rooting

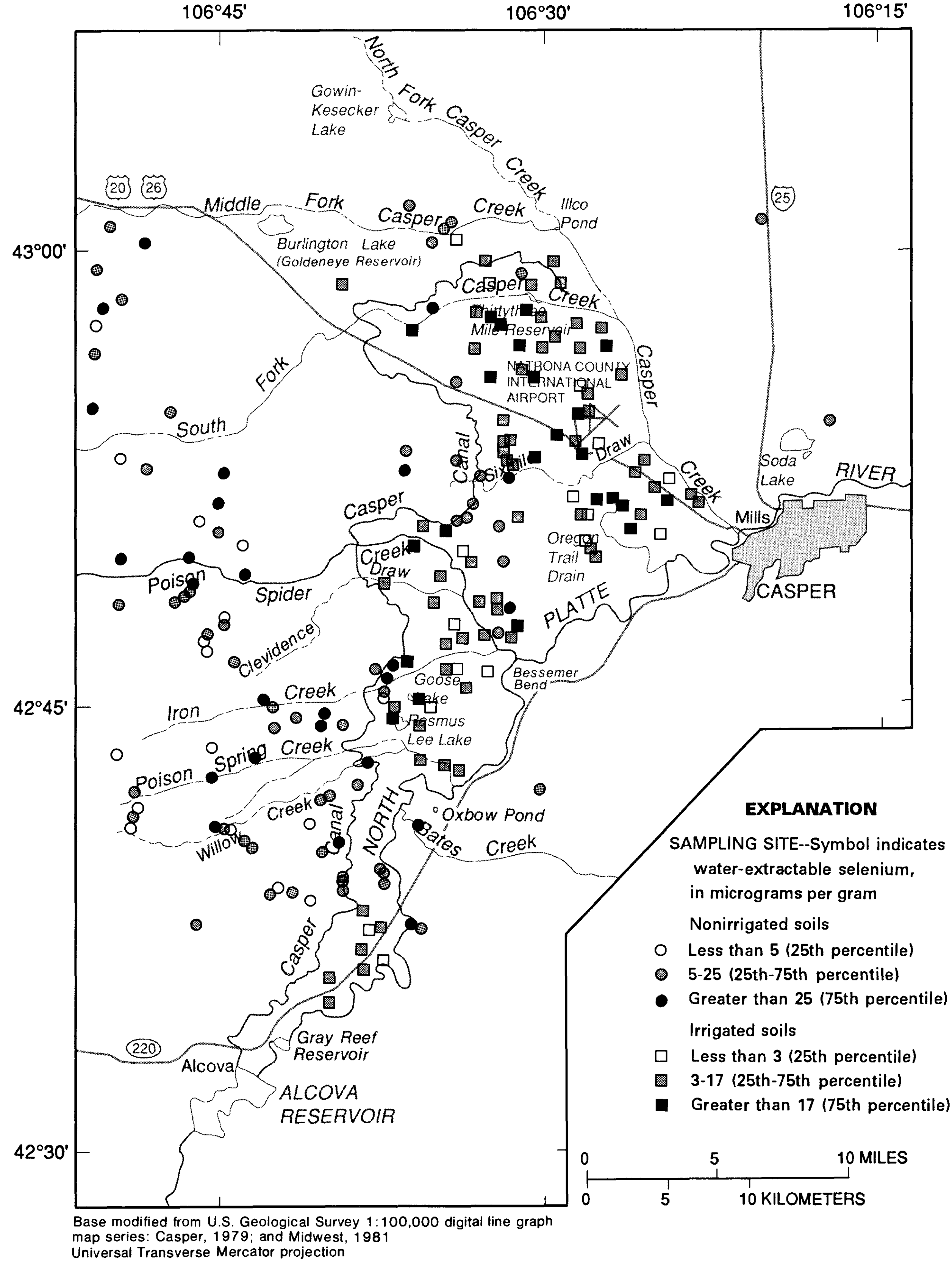


Figure 9.--Location of sampling sites and range of water-extractable selenium concentrations in soil samples.

Table 6.--Correlation coefficients of total selenium concentrations in soil samples, water-extractable selenium in soil samples, and total selenium concentrations in plant samples

[NA, not applicable]

Sample type	Total selenium in soil samples	Water-extractable selenium in soil samples
Water-extractable selenium in nonirrigated soil samples	0.38	NA
Water-extractable selenium in irrigated soil samples	.47	NA
Selenium in big sagebrush samples (nonirrigated soil)	.47	.62
Selenium in alfalfa samples (irrigated soil)	.41	.50

zone. Soil-moisture profiles likely were saturated in early 1989, which resulted in further dilution of soluble selenium. The vigorously growing plants absorbed less total selenium than in the previous year and further diluted that which was absorbed because of the greater production of dry matter. The net effect might explain the large decline in total selenium concentrations in the 1989 alfalfa samples compared to that from the previous year.

These results underscore the importance of irrigation practices on selenium concentrations in crops grown in arid environments and indicate a need to design detailed studies that determine the trends in selenium concentrations in alfalfa during an extended period.

Miscellaneous Soil, Rock Outcrop, and Salt Samples

Rock samples from geologic units were collected where outcrops existed in the study area; most geologic units do not crop out in the study area. None of the rock samples collected contained anomalous concentrations of selenium (Severson and others, 1989b, p. 10). The grab samples of nonirrigated soil all contained small concentrations of selenium and are similar to samples of other nonirrigated soils collected. Two efflorescent (salt crust) samples from the edge of Rasmus Lee Lake contained large concentrations of total selenium (1.0 and 70 $\mu g/g$) that occurred in a mixture of sodium carbonate-bicarbonate salts.

WATER AND BOTTOM SEDIMENT

Selenium concentrations in surface water, ground water, and bottom sediment were assessed to determine concentrations, sources, and transport of selenium in water resources in the study area. Some of the geochemical processes that control mobility and availability of selenium in surface water also were identified. This information is needed to help develop future remediation plans that may be required at the Kendrick area. The availability of selenium is of considerable interest because it is both required by and highly toxic to animals and aquatic birds.

Bottom sediment can bind or complex with selenium through adsorption by clay minerals and organic particulates or reaction with iron species (Lemly and Smith, 1987; McNeal and Balistrieri, 1989). A large percentage of the selenium in aquatic systems can be present in the upper few centimeters of bottom sediment. Oxidizing and mixing processes can solubilize the selenium in bottom sediment. Concentration of selenium in bottom sediment also might occur as a result of bioaccumulation and subsequent incorporation of organic matter as organisms die and settle to the bottom of water bodies. Bottom sediment also can accumulate selenium as a result of selenate reduction at the water-sediment interface. Selenate reduction to elemental selenium by anaerobic bacteria in bottom sediment has been described by Oremland and others (1989). Plant roots and aquatic invertebrates, however, also can be exposed to selenium in bottom sediment.

Sample Collection and Analytical Methods

Water samples collected during this study were collected, preserved, and analyzed according to USGS standardized guidelines and quality control procedures (Knapton, 1985; Friedman and Erdman, 1982). Except for water samples analyzed for total (dissolved plus suspended) selenium, specific conductance, and turbidity, all water samples were passed through a 0.45 μm cellulose filter. Specific conductance of the water samples was determined with a conductivity meter. Turbidity of the water samples was determined nephelometrically (Fishman and Friedman, 1989).

Water samples analyzed for total or dissolved selenium were acidified as soon as possible with concentrated ultrapure nitric acid to a pH less than 2. Selenium concentrations were determined by hydride generation and atomic absorption spectrometry (Fishman and Friedman, 1989). Chloride concentrations were determined by the ferric thiocyanate colorimetric method (Fishman and Friedman, 1989). Selenium and chloride concentrations were determined at the USGS National Water Quality Laboratory in Arvada, Colorado.

The ground-water samples collected by Crist (1974, p. 9) were obtained by pumping wells with an airlift and were analyzed for selenium by the USGS using the colorimetric method described by Magin and others, (1960). During 1988, 51 water samples from domestic wells were collected by the USGS as part of this study. The water samples from domestic wells were collected using existing pumps and were analyzed by the Wyoming Department of Agriculture using the graphite furnace atomic absorption method (U.S. Environmental Protection Agency, 1979). An additional 12 shallow ground-water wells were installed by the USGS in clusters around five sites near Rasmus Lee Lake. A hollow-stem auger was used to drill the well holes. Plastic pipe, 1.5 in. diameter, was installed in each of the well holes. Perforated intervals of pipe were packed with sand and then sealed with bentonite to assure sampling of ground water from the depth of the perforated interval. Water samples from these wells were analyzed for selenium by the USGS National Water Quality Laboratory. The purpose of these wells was to determine water levels and selenium concentrations at depth near Rasmus Lee Lake.

After filtration, water samples to be analyzed for oxygen-18/oxygen-16 (O-18/O-16) and deuterium/hydrogen (D/H) isotopic ratios were preserved with a mercuric-chloride tablet. The O-18/O-16 isotopic ratio of the water samples was determined using a modification of the method developed by Epstein and Mayeda (1953). The D/H isotopic ratio of the water samples was determined by analyzing hydrogen quantitatively extracted from the water (Kendall and Coplen, 1985). The O-18/O-16 and D/H results are reported relative to Vienna Standard Mean Ocean Water (V-SMOW) in the permil notation. The O-18/O-16 and D/H isotopic ratios were determined in the USGS Isotope Fractionation Project Laboratory in Reston, Virginia.

Bottom-sediment samples were collected from the upper 2 to 4 in. of material deposited at the sample sites. At each site, a composite of 6 to 8 subsamples from a small area was collected and thoroughly mixed with a stainless steel spoon in a stainless steel pan. After air drying, samples were sieved at 2 mm to remove material larger than sand size. The sample was then split and two size fractions were analyzed--a less than 63-μm fraction and a less than 2-mm fraction that was ground to 0.15 mm. Sediment sample preparation, analytical techniques, and analytical results have been reported by Harms and others (1990).

North Platte River and Tributaries

Dissolved selenium in the North Platte River was sampled monthly from January to November 1988. Bates Creek and the four tributaries draining the Kendrick area were sampled at their respective junctions with the North Platte River (fig. 10) monthly from January to November 1988, with the exception of July. The tributaries draining the Kendrick area were sampled near or upstream from the Casper Canal monthly from March to November, also with the exception of July. At most of the sites, concurrent samples were collected for analysis of total selenium.

Dissolved and Total Selenium

Virtually all the selenium in streams of the area was present as dissolved selenium. Linear correlation between dissolved and total selenium concentrations in stream-water samples is indicated by the slope of the regression line being nearly one and an r^2 (coefficient of determination) of 0.98 (fig. 11). A Wilcoxon matched-pairs signed rank test did not indicate a significant difference (significance level = 0.10) between dissolved and total selenium concentrations. Little selenium was transported as suspended selenium, even during spring runoff (March 1988) when the tributaries were turbid and had large suspended sediment concentrations. The chemical species and solubility of selenium depend mainly upon the oxidation-reduction potential and pH (Cary and others, 1967; Geering and others, 1968). Selenium solubility increases under oxidized conditions and high pH (Elrashidi and others, 1989). At the pH and oxidized conditions of the water in the tributaries, selenium should be soluble and not precipitated or adsorbed on sediment particles.

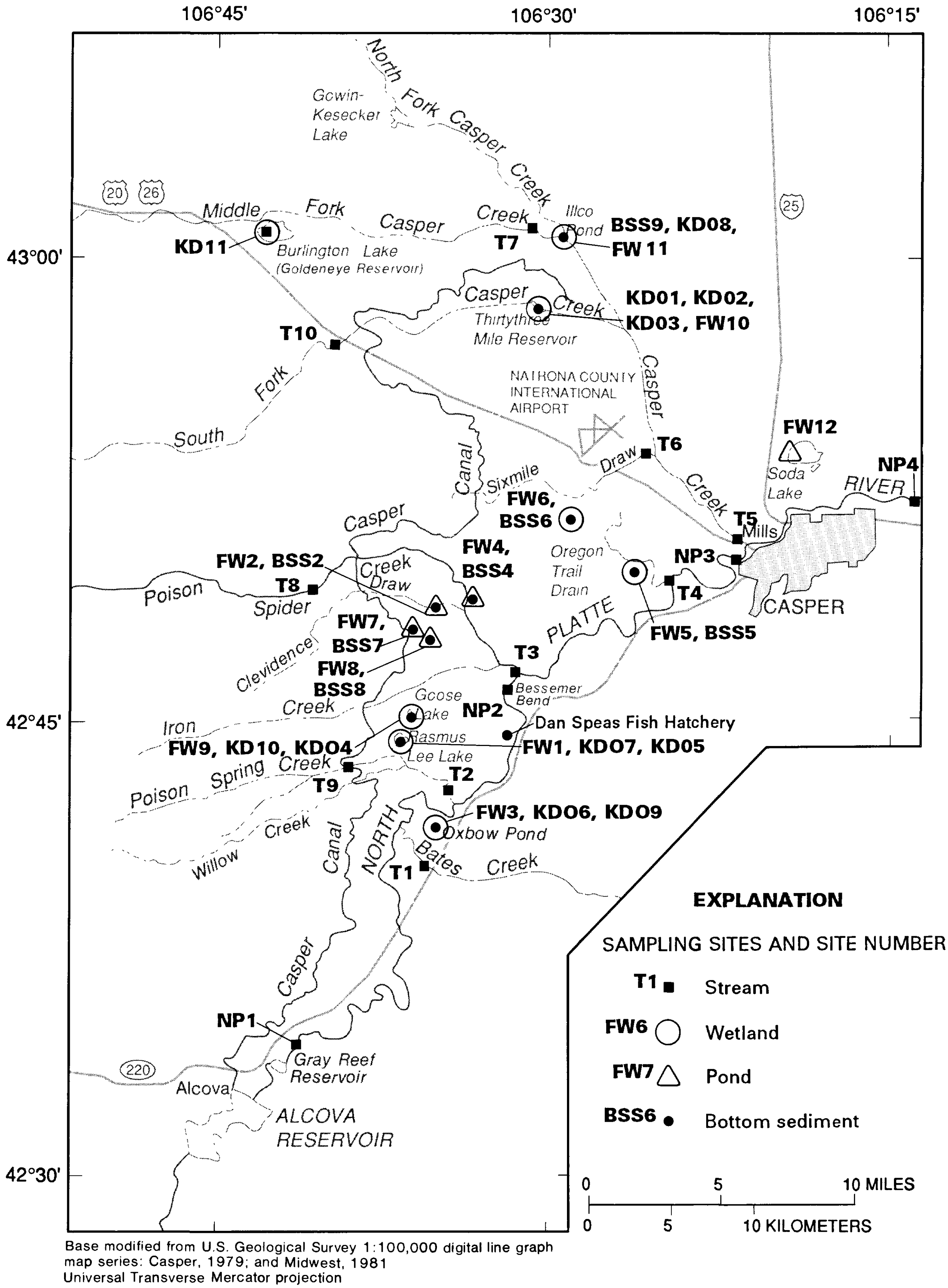


Figure 10.--Location of surface-water and bottom-sediment sampling sites.

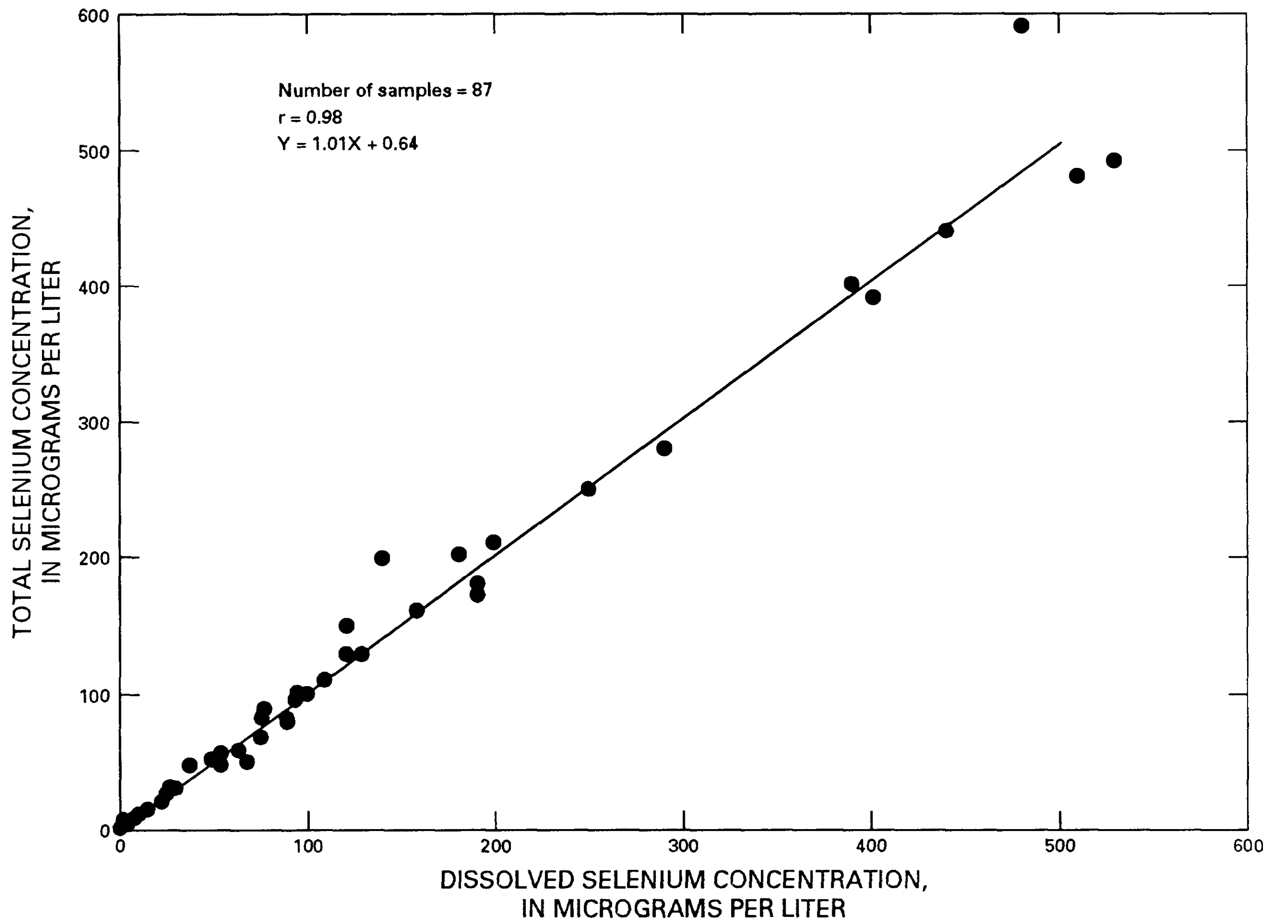


Figure 11.--Relation between dissolved- and total-selenium concentrations in stream-water samples.

North Platte River

Dissolved selenium concentrations in water samples from the North Platte River ranged from less than the reporting limit of 1 μg/L to 10 μg/L. A general increase in dissolved selenium concentrations in the downstream direction is shown in figure 12, which includes data from 1968-89. During the 1988-89 monitoring period, all dissolved selenium concentrations were less than the current maximum contaminant level (MCL)[1] for drinking water of 10 μg/L (U.S. Environmental Protection Agency, 1986) with the exception of one sample from the North Platte River downstream of Casper. That sample contained 10 μg/L and was collected in April 1988, during lowland spring runoff.

[1]MCL is a level (concentration) of contaminant that might cause adverse human health effects if exceeded, and is enforceable for public drinking-water supplies.

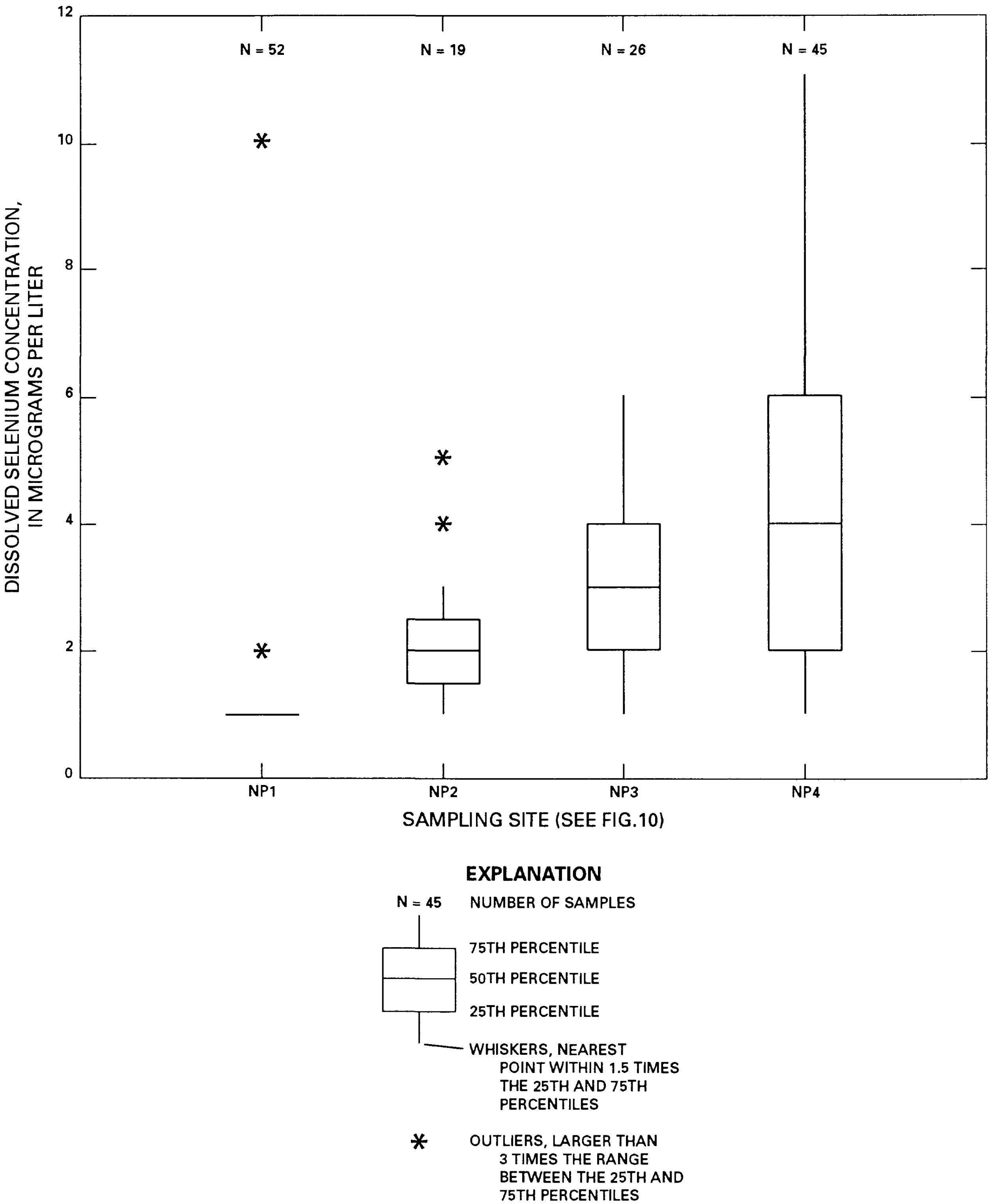


Figure 12.--Dissolved-selenium concentrations in water samples from four sampling sites along the North Platte River (based on 1968-89 data).

Several municipalities, industries, and individual domestic users withdraw water from the North Platte River. The largest municipality is Casper (population about 50,000) which withdraws water from the North Platte between the sampling sites at Mills (site NP3) and downstream of Casper (site NP4). As indicated in figure 12, none of the dissolved selenium concentrations in water samples collected at site NP3 exceeded the MCL of 10 μg/L for drinking water. Larson (1985, p. 65) reported a maximum concentration of dissolved selenium of 14 μg/L for 15 samples collected during 1970-79 at site NP4 downstream of Casper; the maximum concentration was 11 μg/L in 10 samples collected during 1970-79 at the North Platte River at Orin, about 80 river mi downstream from the study area.

The North Platte River is an important fishery for trout, walleye, and other fish and is used for recreation by local residents, commercial outfitters, and tourists. Selenium discharges to the river from the Kendrick area are of interest, because of potential toxicity to fish through bioaccumulation in the aquatic food chain. The Federal freshwater aquatic life criterion for selenium is a 4-day average concentration of 5 μg/L no more than once every 3 years, on the average, and a 1-hour average concentration of 20 μg/L, no more than once every 3 years on the average (U.S. Environmental Protection Agency, 1988). U.S. Environmental Protection Agency water-quality criteria are not enforceable maximum acceptable pollutant concentrations, until their adoption as part of State water-quality standards. Wyoming has not adopted a selenium criterion for freshwater aquatic life.

Cumulative frequency distributions of selenium concentrations in water samples collected at two sites along the North Platte River (fig. 13) were used to estimate the proportion of samples that exceeded the Federal freshwater aquatic life criterion for selenium. Twenty-six water samples analyzed for total selenium were used for site NP3 at Mills and 45 water samples analyzed for dissolved selenium were used for site NP4 downstream of Casper. The water samples were collected at both sites intermittently from 1968-89.

The cumulative frequency plots (fig. 13) show that the chronic 4-day mean aquatic life criterion of 5 μg/L for selenium was exceeded by over 30 percent of the samples collected for total selenium at site NP3, and by 50 percent of the samples collected for dissolved selenium at site NP4 downstream of Casper. The 4-day mean selenium concentrations at site NP3 exceeded the 5 μg/L chronic aquatic life criterion 5 times during a 50-day monitoring period from March 10 to April 28, 1989 (table 7). Selenium source areas in the Kendrick area are contributing selenium to the North Platte River that could result in selenium toxicity directly to fish or through bioaccumulation in the aquatic food chain. Results of selenium sampling in biota are presented later in this report.

Tributaries

Five major tributaries to the North Platte River were sampled during 1988 at about monthly intervals. The four tributaries to the North Platte River draining the Kendrick area receive nearly all of their selenium from the Kendrick area. For example, all eight water samples collected from Poison Spring Creek at site T9 just inside the western boundary of the Kendrick area contained selenium concentrations less than the reporting limit of 1 μg/L, compared to a median selenium concentration of 92 μg/L in water samples from Poison Spring Creek at site T2 downstream of the Kendrick area (table 8). A

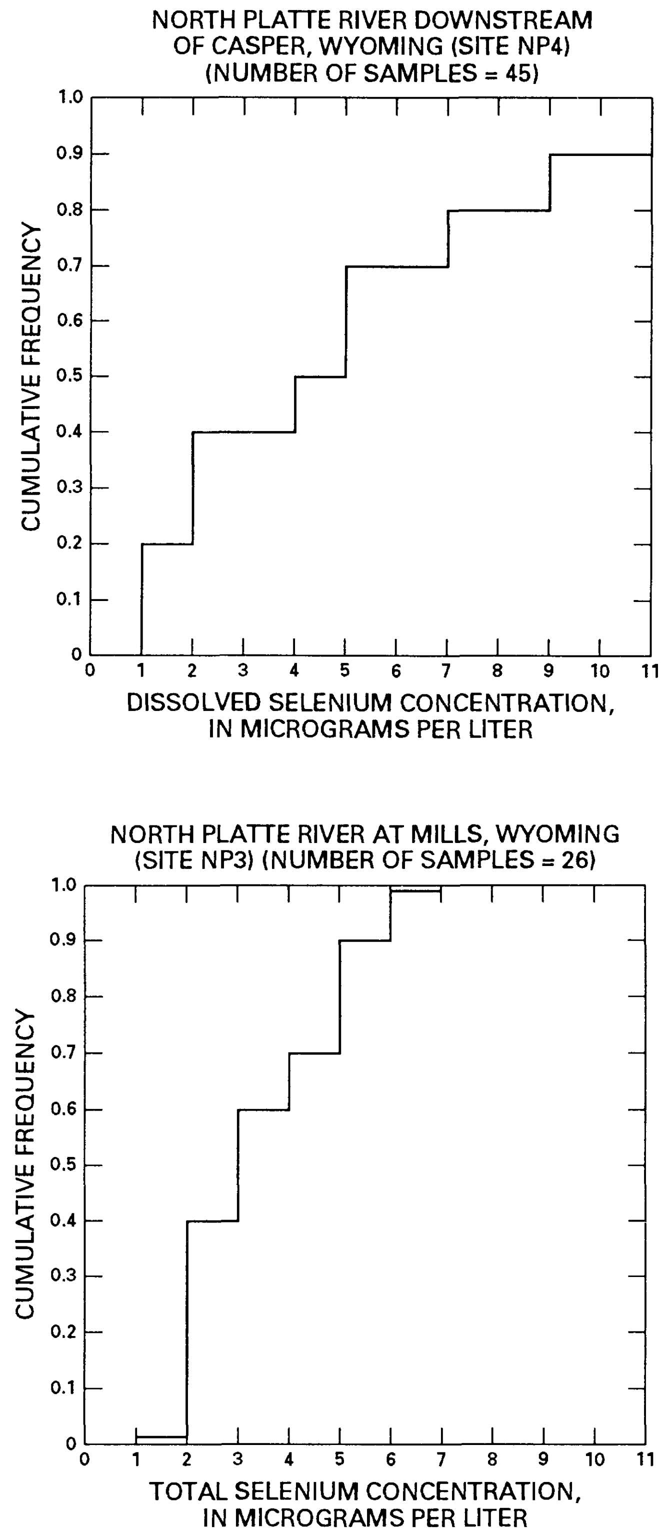


Figure 13.--Cumulative frequency distributions for selenium concentrations in water samples from monitoring sites NP3 and NP4 along the North Platte River (based on 1968-89 data).

Table 7.--Sampling periods that exceeded the 5 μg/L chronic aquatic life criterion, 4-day mean concentration of total selenium in water samples from the North Platte River at Mills (site NP3), during March 10 through April 28, 1989

Dates of sampling period in 1989	Four-day mean concentration of total selenium, in micrograms per liter
3/13 to 3/16	5.5
3/20 to 3/23	5.8
3/27 to 3/30	6.0
4/04 to 4/07	6.0
4/10 to 4/13	5.2

Table 8.--Total selenium concentrations in water samples from and total selenium discharges of tributaries to the North Platte River during 1988

[N, number of samples; --, not computed; <, less than]

Site number (fig. 10)	Site name	Selenium concentration, in micrograms per liter				Selenium discharge, in kilograms per day			
		N	Maximum	Minimum	Median	N	Maximum	Minimum	Median
T9	Poison Spring Creek (upstream)	8	<1	<1	<1	0	--	--	--
T2	Poison Spring Creek (downstream)	10	160	28	92	10	0.685	0.180	0.360
T8	Poison Spider Creek (upstream)	8	12	7	8.5	7	.138	.012	.048
T3	Poison Spider Creek (downstream)	11	90	31	68	10	2.96	1.77	1.96
T4	Oregon Trail Drain (downstream)	17	530	12	200	13	2.91	.252	.849
T7	Middle Fork Casper Creek (upstream)	4	4	<1	<1	1	.003	.003	--
T6	Sixmile Draw (downstream)	5	390	55	190	5	1.87	.935	1.28
T5	Casper Creek (downstream)	11	190	1	100	10	7.49	.027	2.61
T1	Bates Creek (downstream)	10	8	1	6	10	.675	.085	.127

similar increase in concentrations was noted in water samples from Poison Spider Creek; the median concentration was 8.5 μg/L at site T8 upstream of the Kendrick area and 68 μg/L at site T3 downstream. Oregon Trail Drain originates in the Kendrick area. Casper Creek has three forks near the upstream boundary of the Kendrick area, but the South Fork Casper Creek and the North Fork Casper Creek did not flow and were not sampled. The Middle Fork Casper Creek was sampled at site T7 four times, but only one sample contained total selenium concentration (4 μg/L) larger than the reporting limit. The median concentration of total selenium in water samples from Casper Creek downstream of the Kendrick area at site T5 was 100 μg/L.

During this study, the maximum total selenium concentration in water samples from tributaries to the North Platte River was 530 μg/L in a sample collected from Oregon Trail Drain; the median concentration in 17 samples from Oregon Trail Drain was 200 μg/L (fig. 14). Median concentrations of total selenium in water samples from the other three tributaries draining the Kendrick area exceeded the MCL of 10 μg/L for drinking water (U.S. Environmental Protection Agency, 1989); however, it is unlikely that these streams are used as a source of drinking water. Virtually all of the water samples collected from the four tributaries at their junctions with the North Platte River contained total selenium concentrations exceeding the 5 μg/L freshwater aquatic life criterion. The only other major tributary to the North Platte River in the study area is Bates Creek, which does not drain the Kendrick area (fig. 1). Total selenium concentrations in water samples collected from Bates Creek during 1988 ranged from 1 to 8 μg/L.

Seasonal variations in selenium concentration were noted at the five major tributaries to the North Platte River sampled during this study. The minimum concentrations coincided with the maximum streamflow, which generally occurred during spring runoff in March. For example, figure 15 shows this inverse relation for Poison Spring Creek. The relation between concentration and streamflow for the major tributaries also is indicated by a coefficient of determination (r^2) of: Bates Creek, 0.58; Poison Spring Creek, 0.54; Poison Spider Creek, 0.63; Oregon Trail Drain, 0.57; and Casper Creek, 0.33. The r^2 from Casper Creek is smaller than the others, which might be related to the large selenium concentrations detected in soil samples described elsewhere in this report.

The median concentrations of selenium in water samples collected during the current study (1988) were larger than the median concentrations in water samples collected from the same five tributaries during previous studies (fig. 14). As noted previously, the precipitation in 1988 (6.6 in.) was only about one-half of average for 1937-88 and temperatures were slightly above average. These two climatic factors might have increased selenium concentrations through less dilution because of less runoff and increased evaporation. In addition, during dry periods, an increased percentage of ground-water base flow would increase selenium concentrations in surface-water samples.

Selenium Discharges

During 1988, concurrent measurements of total selenium and stream discharge were made for eight sampling periods for all five major tributaries entering the North Platte River from Alcova Reservoir to the site downstream of Casper (fig. 10). The major tributaries accounted for an average of

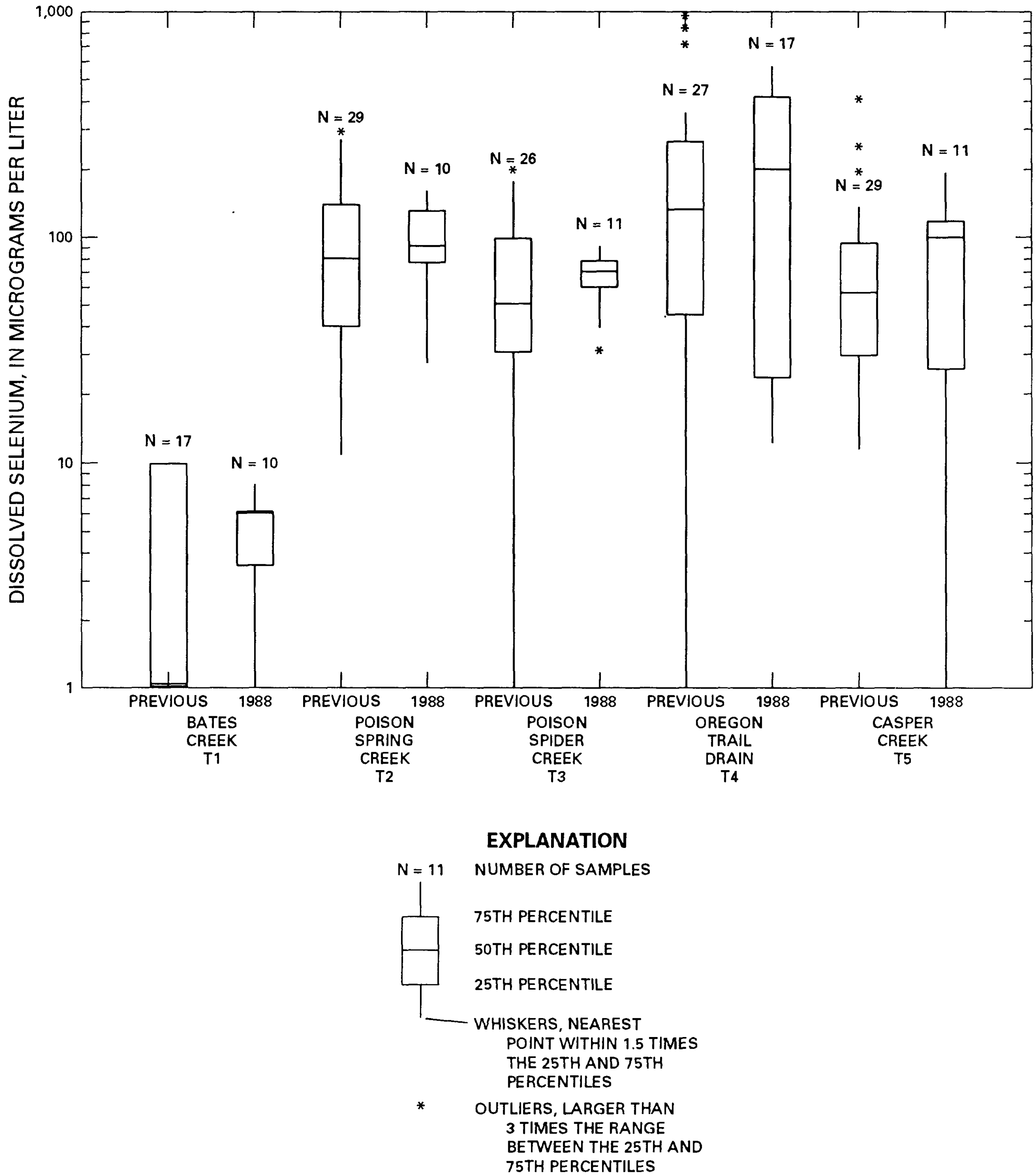


Figure 14.--Dissolved-selenium concentrations in water samples from tributaries to the North Platte River from previous studies and in 1988.

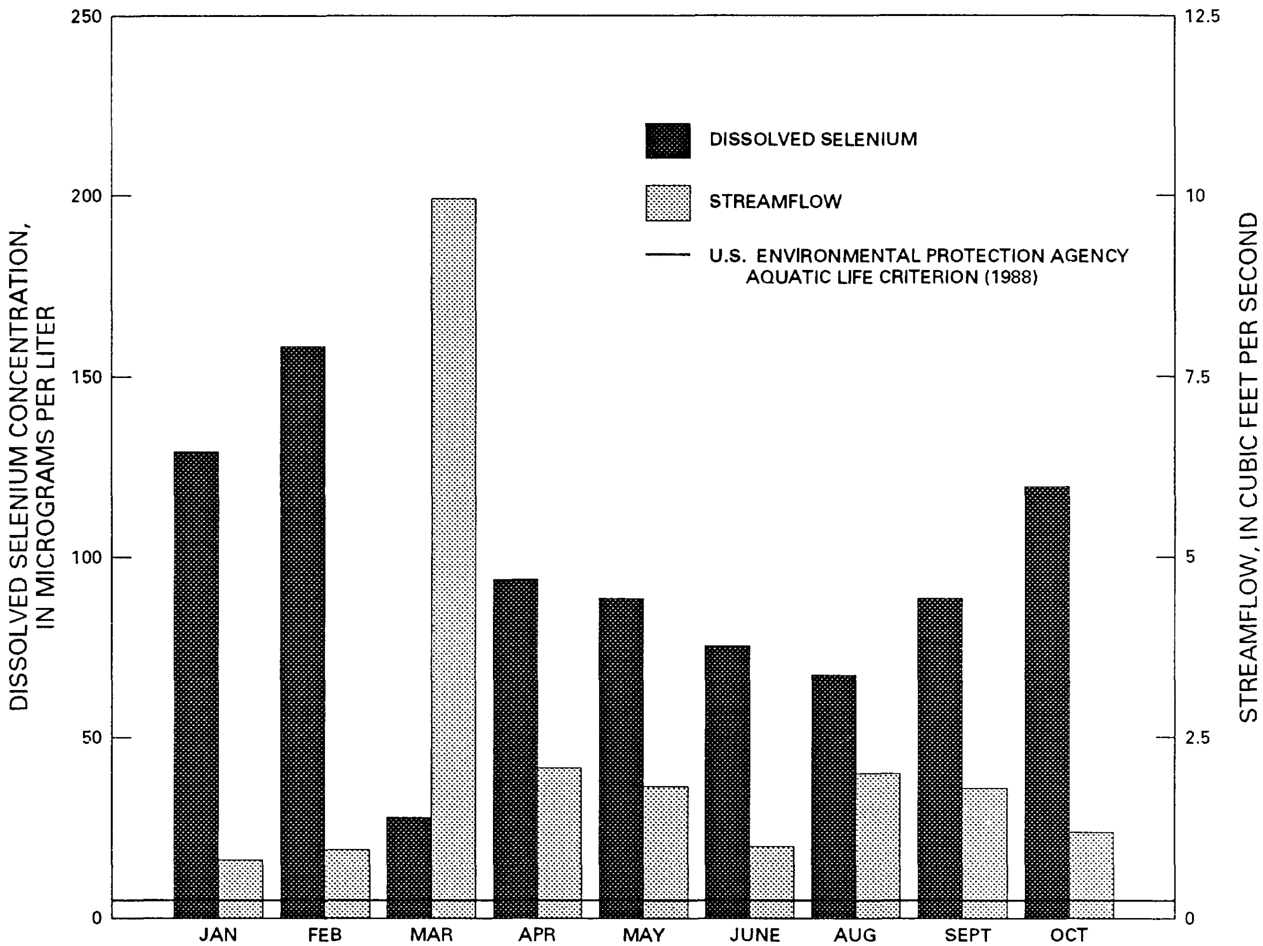


Figure 15.--Dissolved-selenium concentrations in water samples from and streamflow in Poison Spring Creek, 1988.

52 percent of the total selenium discharge measured at the site downstream of Casper. The largest selenium discharge from the Kendrick area, during the months sampled, occurred during May. The selenium discharges in the North Platte River and the major tributaries are shown in figure 16.

Four of the five tributaries sampled along this reach of the North Platte River drain the Kendrick area (fig. 10). Bates Creek, which drains areas south of the Kendrick area, contributed less than 2 percent of the total selenium discharge during the 1988 sampling period. The Casper Creek drainage basin, which contains the largest selenium anomaly identified in the soil, plant, and irrigation drainwater sampling programs, contributed the largest measured selenium discharge of the five tributary sites to the North Platte River during the monitoring period. Poison Spider Creek contributed the second largest selenium discharge to the North Platte River (fig. 16).

Large temporal variations can occur in total selenium concentrations and stream discharges. The data in figure 16 are from individual sample collections and concurrent discharge measurements obtained at the time of sampling. These measurements are assumed to indicate general trends in total selenium discharge. A large percentage of total selenium discharge (as much as 57 percent in September) in the North Platte River below Casper is unexplained by selenium discharged at the North Platte River above Alcova or major tributaries.

The effects of the selenium discharge contributed by the tributaries to the North Platte River vary with the streamflow in the river. For example, the maximum concentration of dissolved selenium in water samples collected in eight months of 1988 from the North Platte River downstream of Casper (site NP4) was 10 μg/L, on April 8, 1988. At the same time, the selenium discharge at that site was 13.5 kg/d, slightly less than the average of 14.7 kg/d in 1988. The concentration of selenium in the river was large and the streamflow was small (552 ft^3/s) for this river. During the 1988 sampling, the selenium discharge of the North Platte River downstream of Casper (site NP4) ranged from 7.8 kg/d in June to 36.2 kg/d in September; streamflow ranged from 552 ft^3/s in April to 3,240 ft^3/s in August. In eight previous water samples, collected during 1974-86, the selenium discharge ranged from 14.7 kg/d to 50.8 kg/d and averaged 24.5 kg/d.

The selenium discharge in the tributaries draining the Kendrick area originated primarily in the Kendrick area. This was a function of much smaller selenium concentrations and streamflows in the tributaries upstream from the Kendrick area than downstream. For example, the median selenium discharge in Poison Spider Creek was 0.048 kg/d upstream of the Kendrick area (site T8) and 1.96 kg/d downstream (site T3) (table 8). Selenium discharge data from Sixmile Draw, a tributary to Casper Creek, which originates in the study area, indicate about one-half of the selenium discharge of Casper Creek is attributable to Sixmile Draw, on the basis of median discharges (table 8).

Drainwater

Irrigation drainwater consists of a combination of shallow ground water and excess irrigation water that might flow across the surface of fields during flood irrigation. During June and August 1988, samples of irrigation drainwater were collected from constructed irrigation drains and intermittent streams which drain irrigated fields throughout the Kendrick area. A total of

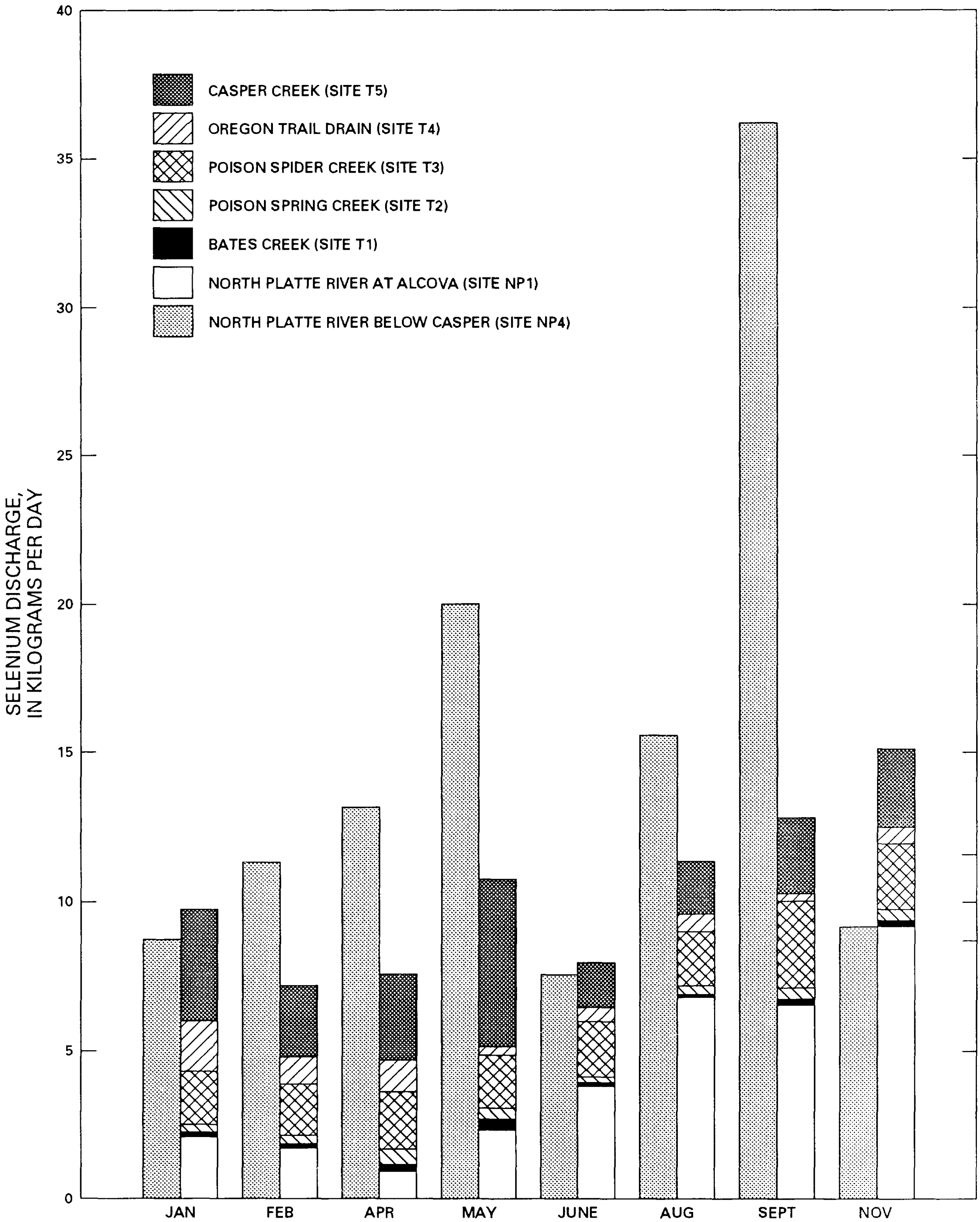


Figure 16.--Selenium discharges from the North Platte River and from tributaries to the North Platte River between Alcova Reservoir and Casper, 1988.

102 irrigation drainwater samples from 51 sites was collected and analyzed during the 1988 sampling effort. The location and percentile ranges of measured selenium concentrations in the irrigation drainwater samples are shown in figure 17.

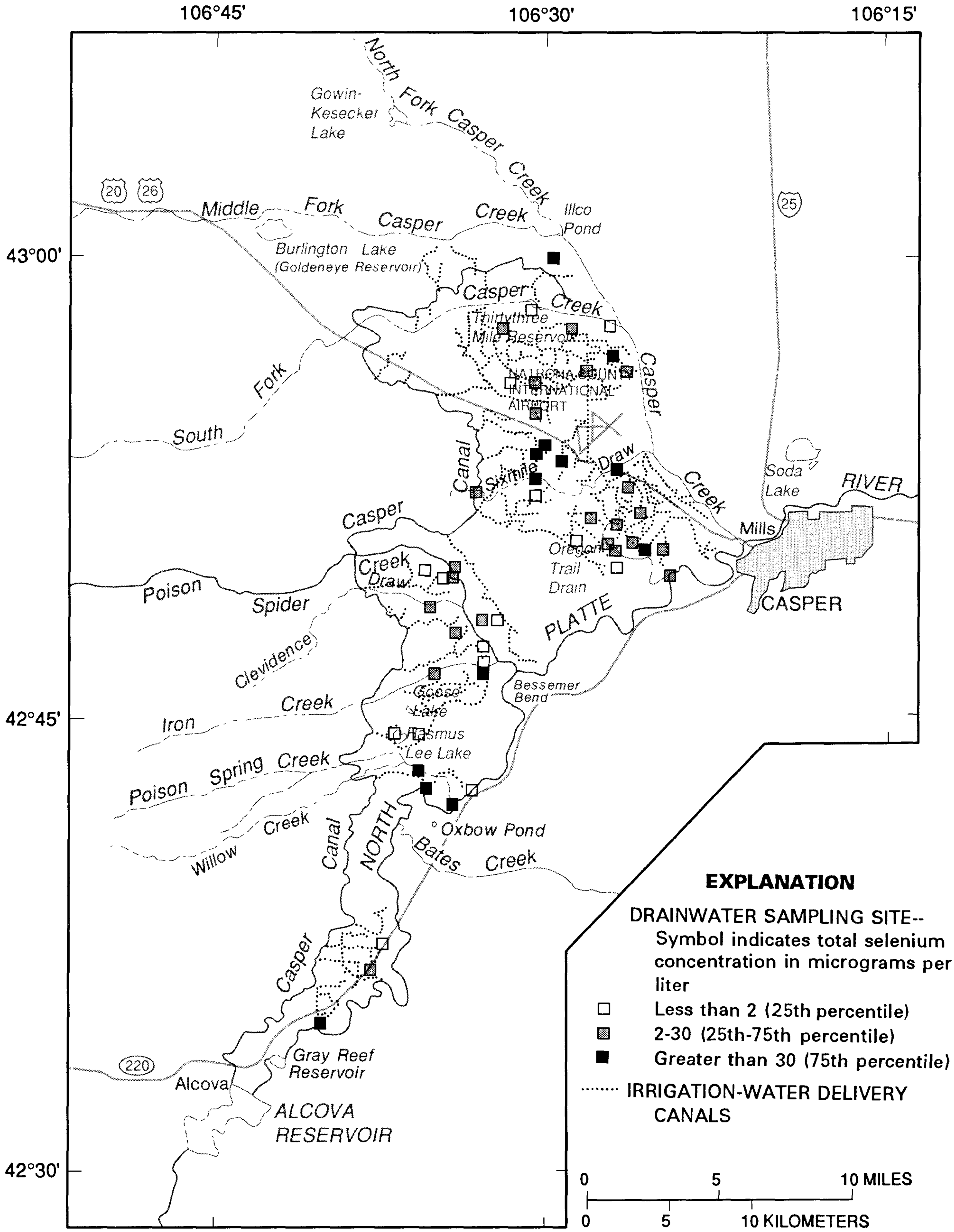
Seasonal trends in the chemical data from drainwater samples were evaluated using scatter plots and a nonparametric statistical test. Most of the paired sampling points in figure 18 plot to the right of the line of equal concentration, indicating that selenium concentrations were larger during June than August. To verify this apparent difference, a Wilcoxon matched-pairs signed rank test (Hollander and Wolfe, 1973, p. 27) was applied to the major-ion and selenium data collected during the two sampling times. The Wilcoxon matched-pairs test uses the size differences between the paired samples in addition to the direction of change between sampling periods to determine if a significant difference exists.

According to the results of the Wilcoxon matched-pairs signed rank test, drainwater samples had a statistically larger selenium concentration (significance level = 0.01) during the June sampling period (table 9). In the June sampling period, the median selenium concentration was 10 μg/L compared to 5 μg/L during the August sampling period. Specific conductance, magnesium, sodium, and sulfate were significantly larger (significance level = 0.10) during the June sampling period (table 9). Larger values for specific conductance, and larger concentrations of selenium, magnesium, sodium, and sulfate indicate that salts accumulated in the soil since the previous irrigation season are flushed from the soil by irrigation water applied during the early part of the irrigation season.

Samples have been collected intermittently at the outlet of Oregon Trail Drain during 1968-86 and at about daily intervals during March through April 1988. The LOWESS (which stands for locally weighted regression, scatter-plot smoothing) technique (Chambers and others, 1983) was applied to the data from Oregon Trail Drain to indicate the changes in selenium concentrations. LOWESS is a statistical method that uses weighted least squares to calculate smoothed values from the data. The LOWESS line can have rapid changes in curvature, whereas the line resulting from polynomial regression cannot show such changes.

The data from Oregon Trail Drain were ordered by the Julian day of collection, and the LOWESS technique was applied to the data. The data values and the LOWESS-smoothed line are shown in figure 19. The smallest values on the LOWESS-smoothed line for selenium concentration are for July through August after the initial flushing of soils by irrigation water in the spring and early summer and during continued irrigation during the summer and early fall. The application of irrigation water during the summer months has been shown to dilute selenium concentrations in ground water (Crist, 1974). The large selenium concentrations detected in water samples collected from September through May could be the result of an increased percentage of ground water with large selenium concentrations draining the irrigated areas.

Flushing of large selenium concentrations from soil before and during the early part of irrigation season has been observed in other irrigation projects. Data compiled by Anderson and others (1961) found the largest selenium discharge to the Gunnison River from an irrigation project in Colorado occurred during the early part of the irrigation season. Salts that



Base modified from U.S. Geological Survey 1:100,000 digital line graph map series: Casper, 1979; and Midwest, 1981
Universal Transverse Mercator projection

Figure 17.--Location of drainwater sampling sites and range of selenium concentrations in drainwater samples.

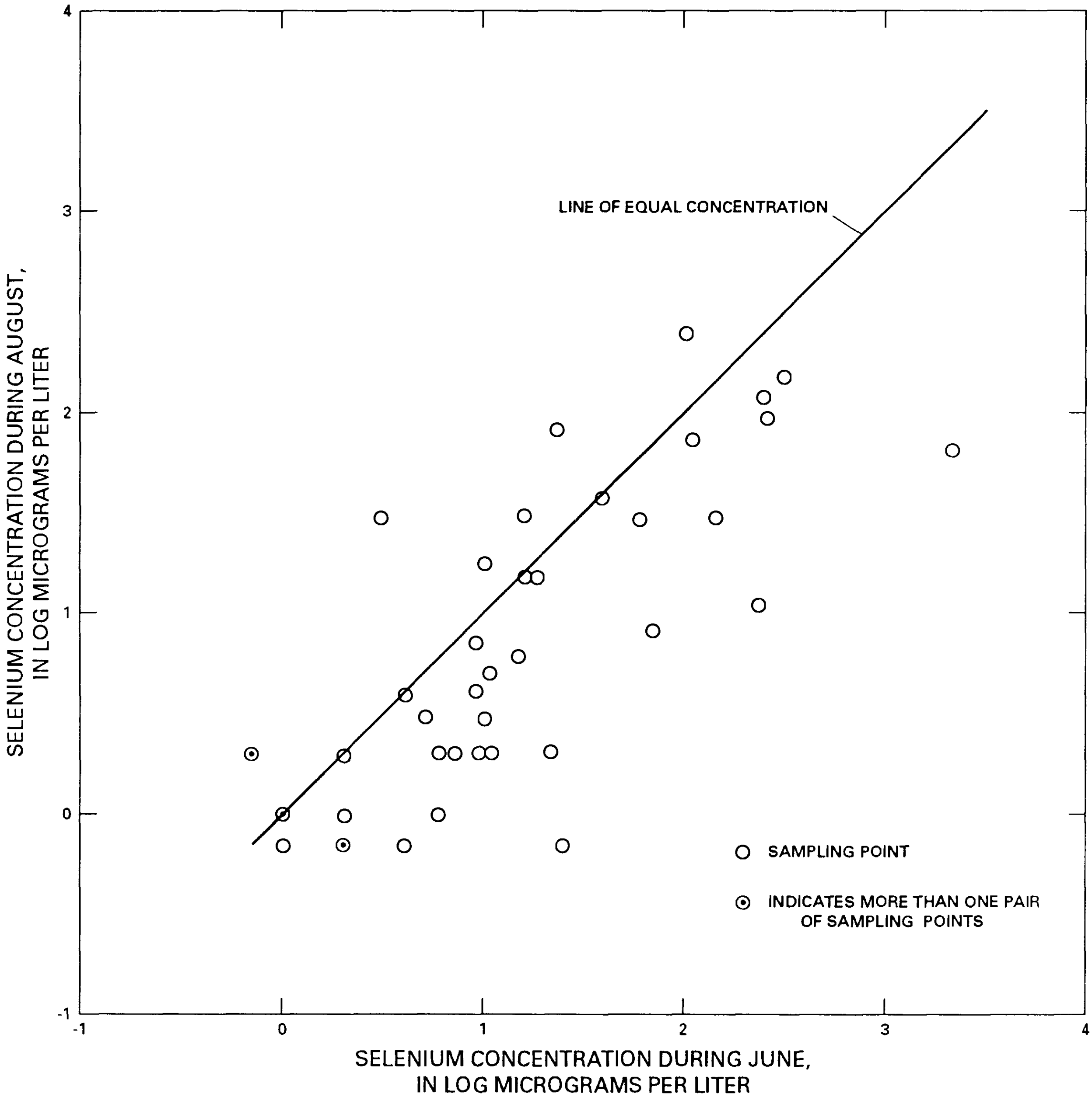


Figure 18.--Selenium concentrations in paired samples of irrigation drainwater collected in June and August 1988.

Table 9.--Median and Z-test statistic calculated by the Wilcoxon matched-pairs signed rank test for 43 paired samples of irrigation drainwater collected in June and August 1988

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter]

Property or chemical constituent	Median concentration June	Median concentration August	Z-test statistic	Significant at listed confidence level
pH	8	8	-1.59	Not significant
Specific conductance (μS/cm)	1,590	1,360	-2.43	0.10
Calcium (mg/L)	120	96	-1.28	Not significant
Magnesium (mg/L)	72	53	-1.99	.10
Sodium (mg/L)	190	130	-2.12	.10
Potassium (mg/L)	7	7	-0.28	Not significant
Alkalinity (mg/L)	254	194	-1.29	Not significant
Sulfate (mg/L)	710	500	-1.71	.10
Chloride (mg/L)	18	15	-0.83	Not significant
Selenium (μg/L)	10	5	-3.15	.01

accumulated along the drainage ditches in Colorado since the previous fall were determined to contain large concentrations of selenium. Salt crust samples collected from the Kendrick area contained selenium concentrations as large as 70 μg/g (Severson and others, 1989b).

Wetlands and Ponded Water

Selenium concentrations were monitored during this study at six wetlands in and adjacent to the Kendrick area where bird use had been noted during onsite observations (fig. 10). Four of the wetlands are in or near the Kendrick area and include Rasmus Lee Lake, Goose Lake, Thirtythree Mile Reservoir, and Illco Pond. Illco Pond is a small pond just south of the junction of North Fork Casper Creek and South Fork Casper Creek. "Illco" is not a formal geographic name, but it is used by local residents and personnel working on this study. The two remaining wetlands, Oxbow Pond and Goldeneye Reservoir (Burlington Reservoir), were outside the Kendrick area and were used as reference sites. Oxbow Pond, which is not identified officially on any USGS map series, is a small body of water east of the junction of Bates Creek and the North Platte River. The official name of Goldeneye Reservoir is "Burlington Reservoir"; however, because road signs, project personnel, and residents of the Casper area identify it as Goldeneye Reservoir, this name will be used in this report.

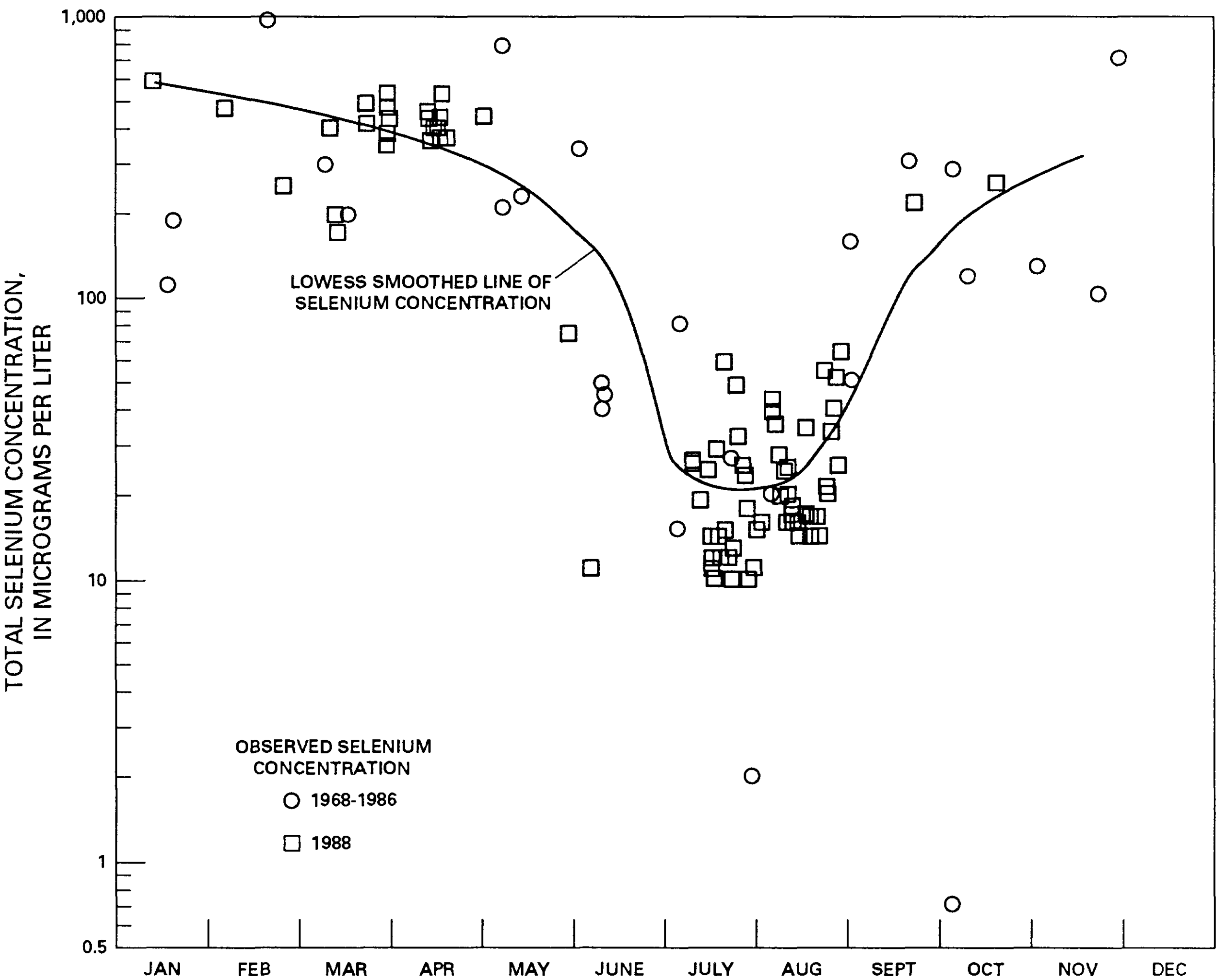


Figure 19.--Observed total-selenium concentrations and LOWESS-smoothed line of total-selenium concentrations in water samples from the Oregon Trail Drain.

Water samples collected at the four monitored wetlands in or near the Kendrick area contained median dissolved selenium concentrations greater than the Federal freshwater aquatic life criterion of 5 μg/L selenium (U.S. Environmental Protection Agency, 1988). Water samples from Rasmus Lee and Goose Lakes contained the largest median dissolved selenium concentrations. The median dissolved selenium concentrations were 38 μg/L in water samples from Rasmus Lee Lake and 54 μg/L in water samples from Goose Lake. The median dissolved selenium concentrations in water samples from the two wetlands outside the Kendrick area, Oxbow Pond and Goldeneye Reservoir, were equal to or less than 1 μg/L (fig. 20).

In addition to the data collected at the six monitored wetlands, water samples were collected from seven ponded-water sites which potentially could provide habitat to aquatic birds. The locations of these sites are shown in figure 10. The water samples were collected during July 1988. Except for site FW7, the dissolved selenium concentration was less than the 5 μg/L Federal freshwater aquatic life criterion for selenium (U.S. Environmental Protection Agency, 1988). Site FW7 had a dissolved selenium concentration of 6 μg/L and is located upstream of any irrigated land, about 0.25 mi east of the Casper Canal in the Poison Spider Creek drainage basin.

Bottom Sediment

Twenty bottom-sediment samples were collected from reservoirs, lakes, and ponds in the study area. More than one bottom-sediment sample was collected at several of the sampling sites shown in figure 10.

A concentration of selenium in the less than 63-μm and less than 2-mm size fractions of bottom sediment equal to or greater than 4 μg/g dry weight is a level of concern for fish and wildlife (Lemly and Smith, 1987, p. 9). Six bottom-sediment sampling sites had selenium concentrations larger than 4 μg/g, dry weight in both the less than 63-μm and less than 2-mm size fractions (fig. 21). The largest concentrations of selenium in bottom sediment were detected in samples from Goose Lake (20 to 43 μg/g) (table 10).

The concentrations of selenium in all bottom-sediment samples from the study area (0.3 to 43 μg/g dry weight) are larger than the geometric mean concentration of 0.23 μg/g, determined for soil in the western United States (Shacklette and Boerngen, 1984). Although used for comparison, the B-horizon soil samples collected by Shacklette and Boerngen (1984) are not similar to the reduced bottom-sediment samples collected in this study. All selenium concentrations for less than 63-μm size fraction in bottom-sediment samples in this study were equal to or larger than concentrations reported for streambed sediment from streams in the Northern Great Plains and for the less than 63-μm size fraction in streambed sediment from streams in the Powder River basin of Wyoming (Berrow and Ure, 1989, table 4, p. 224). The median selenium concentration (2.5 μg/g dry weight) for bottom-sediment samples from the Kendrick area was larger than median selenium concentrations of bottom-sediment samples from 17 of 20 irrigation drainage projects from which bottom-sediment samples have been collected (Feltz and others, 1991).

In reducing environments, selenium exists in the selenide or elemental selenium oxidation states and is very insoluble in water (Elrashidi and others, 1989). Thus, selenium enrichment of bottom sediment might be expected in the reduced conditions found at the bottom of reservoirs, lakes, and ponds of the study area.

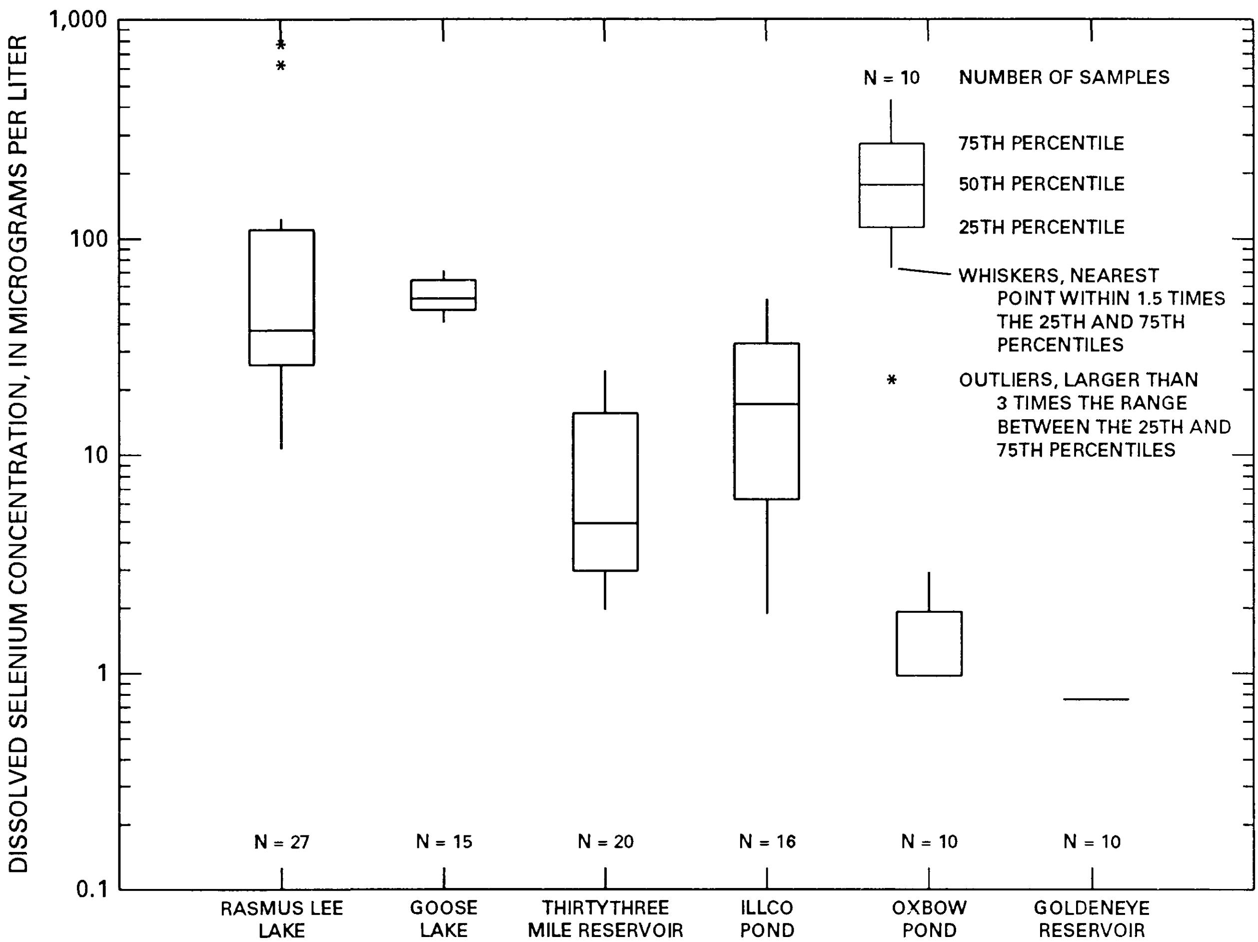
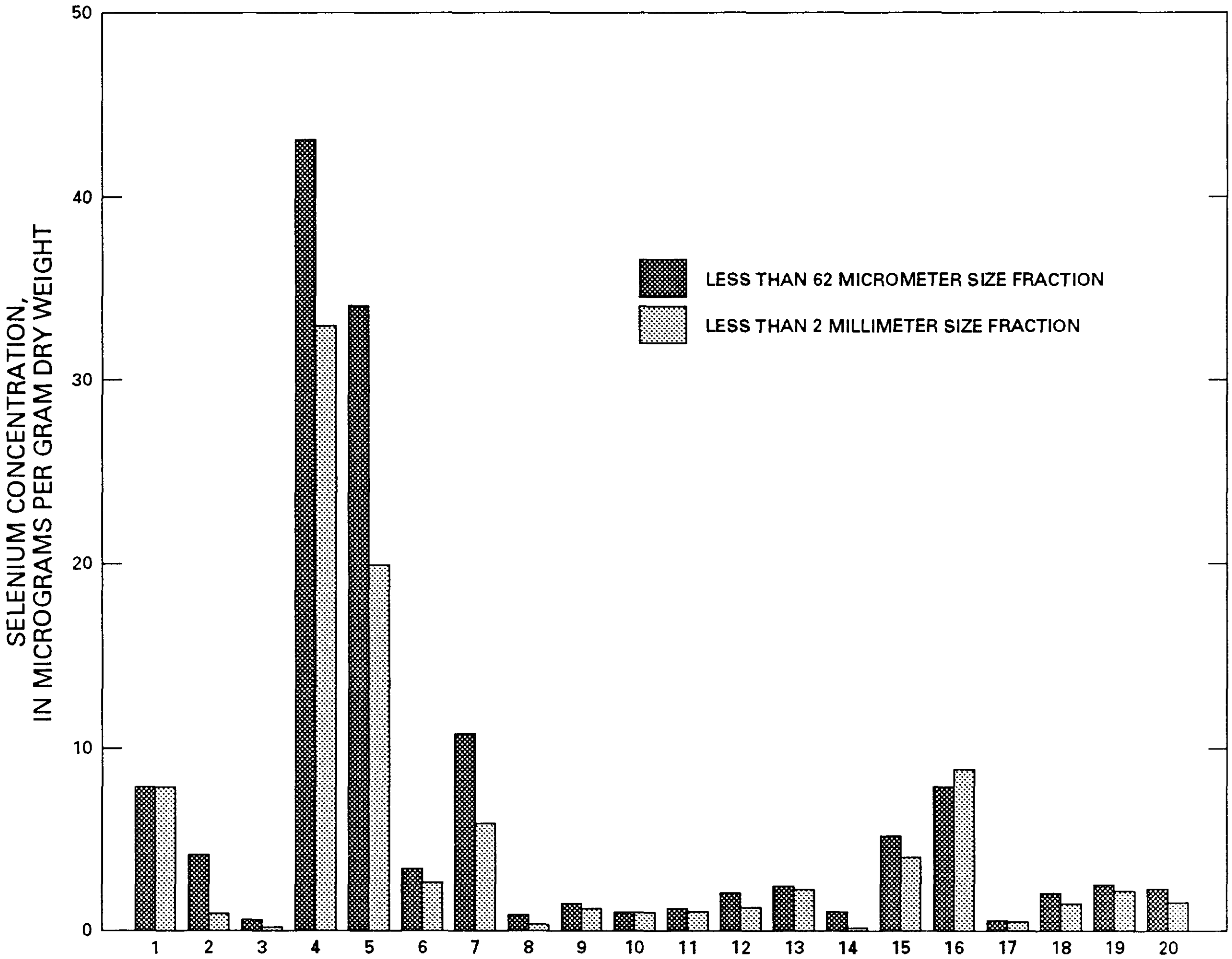


Figure 20.--Dissolved-selenium concentrations in water samples from six monitored wetland sites in and near the Kendrick area, 1988.



EXPLANATION

1 EMIGRANT POND (BSS7)
2 FAA STATION (BSS4)
3 GOLDENEYE RESERVOIR (KD11)
4 GOOSE LAKE, EAST END (KD10)
5 GOOSE LAKE, WEST END (KD04)
6 ILLCO POND (BSS9)
7 ILLCO SEEP, NEAR OUTLET(KD08)
8 LANG RESERVOIR, NORTH (BSS6N)
9 LANG RESERVOIR, SOUTH (BSS6S)
10 ONSTADT POND (BSS2)
11 ONSTADT POND, REPLICATE (BSS2)
12 OXBOW POND (KD09)
13 OXBOW POND, REPLICATE (KD09)
14 POWERLINE POND (BSS5)
15 RASMUS LEE LAKE (KD07)
16 RASMUS LEE LAKE, MIDPOINT (KD05)
17 SHEEP POND (BSS8)
18 THIRTYTHREE MILE RESERVOIR, INLET (KD03)
19 THIRTYTHREE MILE RESERVOIR, MIDPOINT (KD02)
20 THIRTYTHREE MILE RESERVOIR, OUTLET (KD01)

Figure 21.--Selenium concentrations in bottom-sediment samples, 1988. (Site code shown in parentheses refers to locations shown in fig. 10.)

Table 10.--Selenium and organic carbon in bottom-sediment samples

[<63 μm, sample fraction less than 63 microns; <2 mm, sample fraction less than 2 millimeters; data from Harms and others, 1990]

Sampling site	Site number	Selenium, in micrograms per gram, dry weight		Organic carbon, percent	
		<63 μm	<2 mm	<63 μm	<2 mm
Emigrant Pond	BSS7	8.0	8.0	1.40	1.46
FAA Station	BSS4	4.2	1.0	1.83	.32
Goldeneye Reservoir (Burlington Lake)	KD11	.7	.3	1.08	.57
Goose Lake near east end	KD10	43.0	33.0	1.61	1.42
Goose Lake near west shore	KD04	34.0	20.0	.73	.40
Illco Pond	BSS9	3.5	2.6	1.17	1.15
Illco seep near outlet	KD08	11.0	5.9	1.22	.99
Lang Reservoir, north	BSS6n	.9	.4	1.73	1.00
Lang Reservoir, south	BSS6s	1.5	1.2	1.35	1.15
Onstadt Pond	BSS2	1.0	1.0	1.09	.86
Onstadt Pond (replicate sample)	BSS2	1.2	1.0	.84	.66
Oxbow Pond	KD06	2.1	1.3	4.45	3.08
Oxbow Pond (replicate sample)	KD06	2.5	2.2	4.93	4.78
Powerline Pond	BSS5	1.0	.3	2.08	.72
Rasmus Lee Lake	KD07	5.3	4.0	.87	.51
Rasmus Lee Lake, midpoint	KD05	8.0	9.0	2.07	2.05
Sheep Pond	BSS8	.5	.5	.88	.75
Thirtythree Mile Reservoir near inlet	KD01	2.0	1.4	.65	.66
Thirtythree Mile Reservoir near midpoint	KD02	2.5	2.2	.74	.75
Thirtythree Mile Reservoir near outlet	KD03	2.3	1.5	.55	.36

As sediment grain sizes decrease, the surface area per unit weight of material on which trace elements can concentrate increases. Coatings on grains, rather than the grain substrate, can act as collectors of trace elements such as selenium. Horowitz and Elrick (1987, p. 438) determined that selenium concentration was related significantly (significance level = 0.05) to surface coatings of iron and manganese oxides, hydroxides, and organic matter on the grain substrate.

A Wilcoxon matched-pair signed rank test (Hollander and Wolfe, 1973, p. 27) indicated significantly larger (significance level = 0.01) concentrations of selenium and water-extractable boron in the less than 0.63-μm size fraction when compared to the less than 2-mm size fraction of bottom-sediment samples. No significant correlations between concentrations of selenium and iron, manganese, or organic carbon were identified in either size fraction of bottom-sediment samples from the Kendrick area. However, because the analyses of bottom-sediment samples in this study were from total sediment digests, the effect of surface coatings on the grains could not be evaluated.

Naftz and Rice (1989, p. 565) found a strong positive correlation between selenium and organic carbon in mining overburden samples. However, no significant correlations (significance level <0.10) were determined between selenium and total or organic carbon for either size fraction of bottom sediment in the Kendrick area. Selenium and organic carbon concentrations are listed in table 10.

Ground Water

During 1968-70, ground-water samples from 117 wells and 5 springs in the Kendrick area were collected and analyzed for selenium (Crist, 1974, p. 18--26). An additional 51 wells in the Kendrick area were sampled during 1988, by personnel of the State of Wyoming Department of Environmental Quality. About 95 percent of the Crist (1974) data and about 80 percent of the State data were from wells that are 100 ft or less in depth. The sampling locations and observed range of selenium concentrations in ground-water samples are shown in figure 22. Because the data from the water samples collected from wells were used to display ranges of selenium concentrations and not absolute concentrations, the data sets from Crist (1974) and from the State were combined for this study. Where multiple water samples were collected from and analyzed for a well for Crist's data (1974), mean concentrations were used when two water samples were collected, and median concentrations were used when three or more samples were collected.

In an attempt to assess the effects of selenium in ground water on human health, questionnaires from the Natrona County Health Department were submitted to each household at the time the wells were sampled during 1988. The purpose of the questionnaire was to document the food consumption, water use, and medical histories of the residents. However, no questionnaires were returned, so it was impossible for the Health Department to assess any physiological effects of selenium concentrations in the food and water supply on humans living in the Kendrick area.

Ground-water samples with large (greater than 75th percentile range, greater than 140 μg/L) selenium concentrations were collected throughout the Kendrick area. Large selenium concentrations were detected in water samples from wells clustered west of the junction of Casper Creek and the North Platte River (fig. 22). Also in this area, however, selenium concentrations less than 10 μg/L were detected in water samples from several wells. The largest median selenium concentration in ground-water samples in or near the Kendrick area was 50 μg/L, collected from wells in the Poison Spider Creek subbasin (table 29 and fig. 42). About 65 percent of the ground-water samples from the Kendrick area contained selenium concentrations that exceeded the 10 μg/L maximum contaminant level (U.S. Environmental Protection Agency, 1986).

In each hydrologic subbasin in or near the Kendrick area for which data were available (fig. 40), median dissolved selenium concentrations in ground-water samples were larger than median dissolved selenium concentrations in

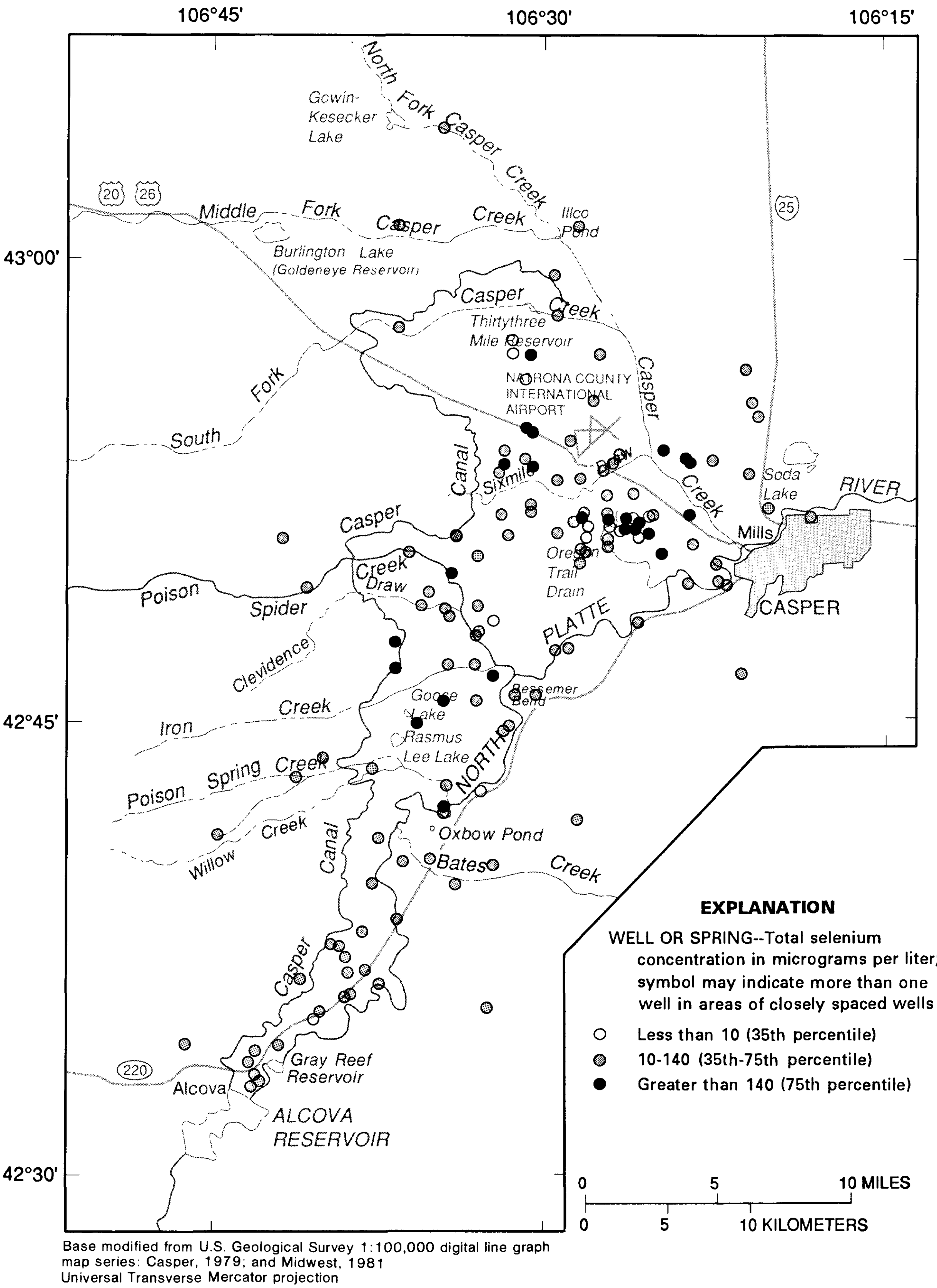


Figure 22.--Location of wells and springs sampled and range of selenium concentrations in ground-water samples; 1968-70 and 1988 (includes data from Crist, 1974, p. 18-26).

drainwater samples (table 29). The Poison Spider Creek subbasin had the largest median dissolved selenium concentration in ground-water samples (50 μg/L) but had the smallest median dissolved selenium concentration in drainwater samples (4.3 μg/L).

Several factors may influence the selenium concentrations in water samples from wells. The depth at which the casing interval in the wells is open in addition to the geologic formation in which the well is completed can have an effect on the selenium concentration of water sampled. Crist (1974, p. 36) noted large seasonal fluctuations of the selenium concentrations in water samples from wells. Selenium concentrations differed in water samples collected by Crist (1974, p. 36) from some wells at different times of the year, indicating that irrigation water diluted the concentration of selenium in the ground water during certain times of the year.

Well-permit files maintained by the Wyoming State Engineer document a variety of details about permitted wells including uses and location of the wells. The well-permit files list 481 wells in and near the Kendrick area with domestic use and 202 wells with stock use identified as the primary use of the wells. Only 51 wells of the 481 domestic-use wells were sampled as part of this investigation. Only 51 well owners responded to a written request for permission to sample their wells. The inclusion of Crist's data (1974), however, gives an indication of the range of selenium concentrations that would be expected with additional sampling. The location of domestic- and stock-use wells are shown in figures 23 and 24.

A series of 13 wells was drilled in 5 clusters near Rasmus Lee Lake (fig. 25). Plastic pipe, 1.5 in. diameter, was installed in each of the well holes for water-level measurements and sampling. The space between the plastic pipe and the well hole was sealed with bentonite above the perforated interval of the pipe, so only ground water from the perforated interval of the pipe was sampled. These wells were installed to allow sample collection to investigate concentrations of selenium in ground water and to determine general direction of ground-water flow around Rasmus Lee Lake. A summary of data from these wells is shown in table 11.

Wells RAS-1 and RAS-2 were near an unlined, flowing irrigation ditch, but water levels and selenium concentration in a water sample from RAS-2 did not indicate a hydraulic connection to the ditch. Well RAS-1 did not contain any water. Well RAS-2 was completed in a sand layer from 17.5 to 22.5 ft; a water sample collected at this well contained a selenium concentration of 2,600 μg/L.

Wells RAS-3 and RAS-4A also were near the same irrigation ditch, and ground water near these wells apparently was hydraulically connected to water in the ditch. The water levels in these two wells were about at the same elevation of the bottom of the ditch. Depth of water in the ditch at the time of the water-level measurements was not recorded. Selenium concentrations were small (from less than 1 to 5 μg/L).

Well RAS-4B was a flowing well. Water levels in wells RAS-5A, RAS-5B, and RAS-6 ranged from 0.6 to 1.7 ft below land surface. The selenium concentration in water samples from wells RAS-4B, RAS-5A, RAS-5B, and RAS-6 ranged from 14,000 to 23,000 μg/L. If this ground water was in hydraulic connection with Rasmus Lee Lake, and if large amounts of this ground water flowed into the lake, larger selenium concentrations might be expected in the lake.

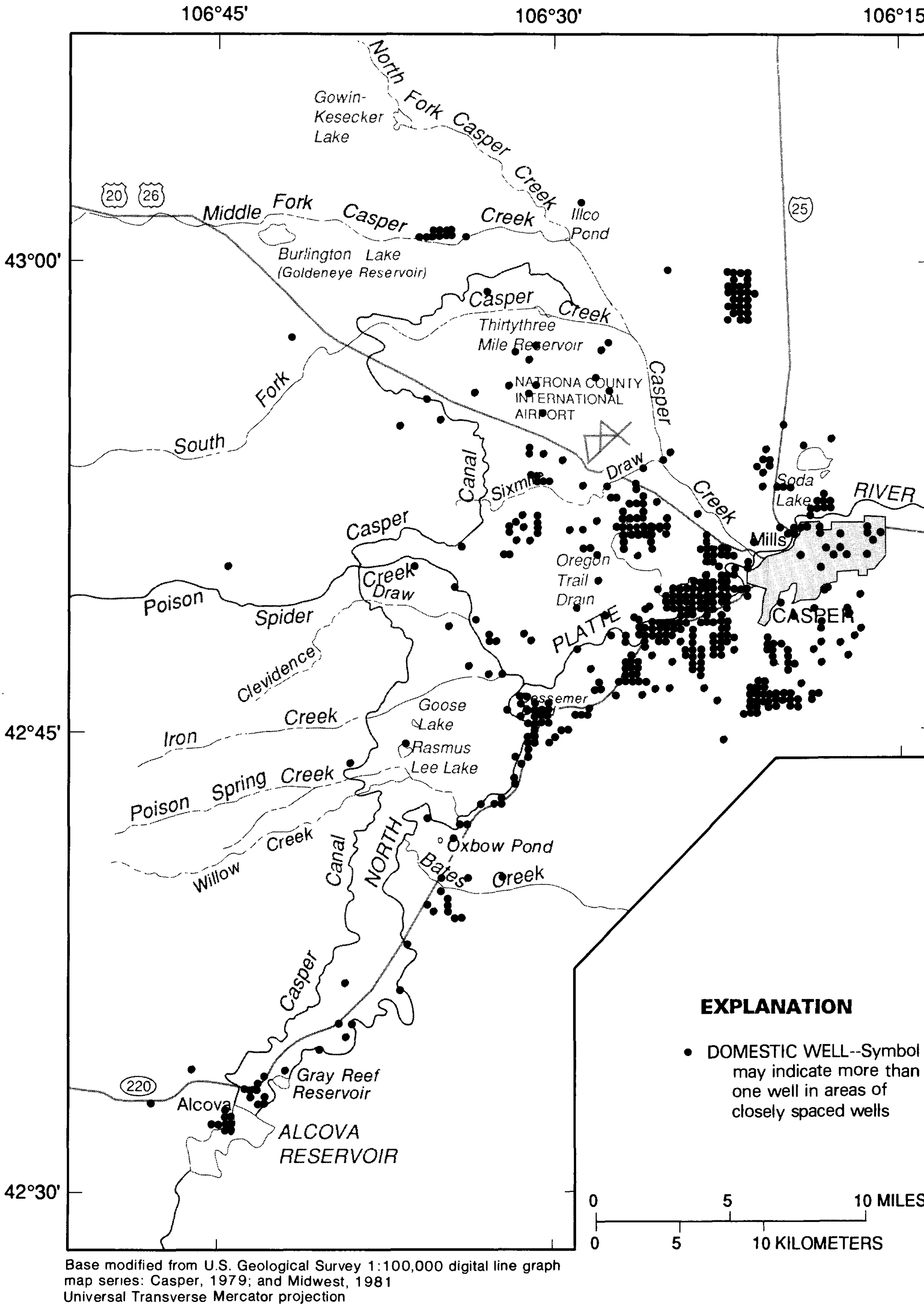


Figure 23.--Location of domestic-use wells identified from the Wyoming State Engineer well-permit files during 1988. (Location plotted to the nearest quarter section.)

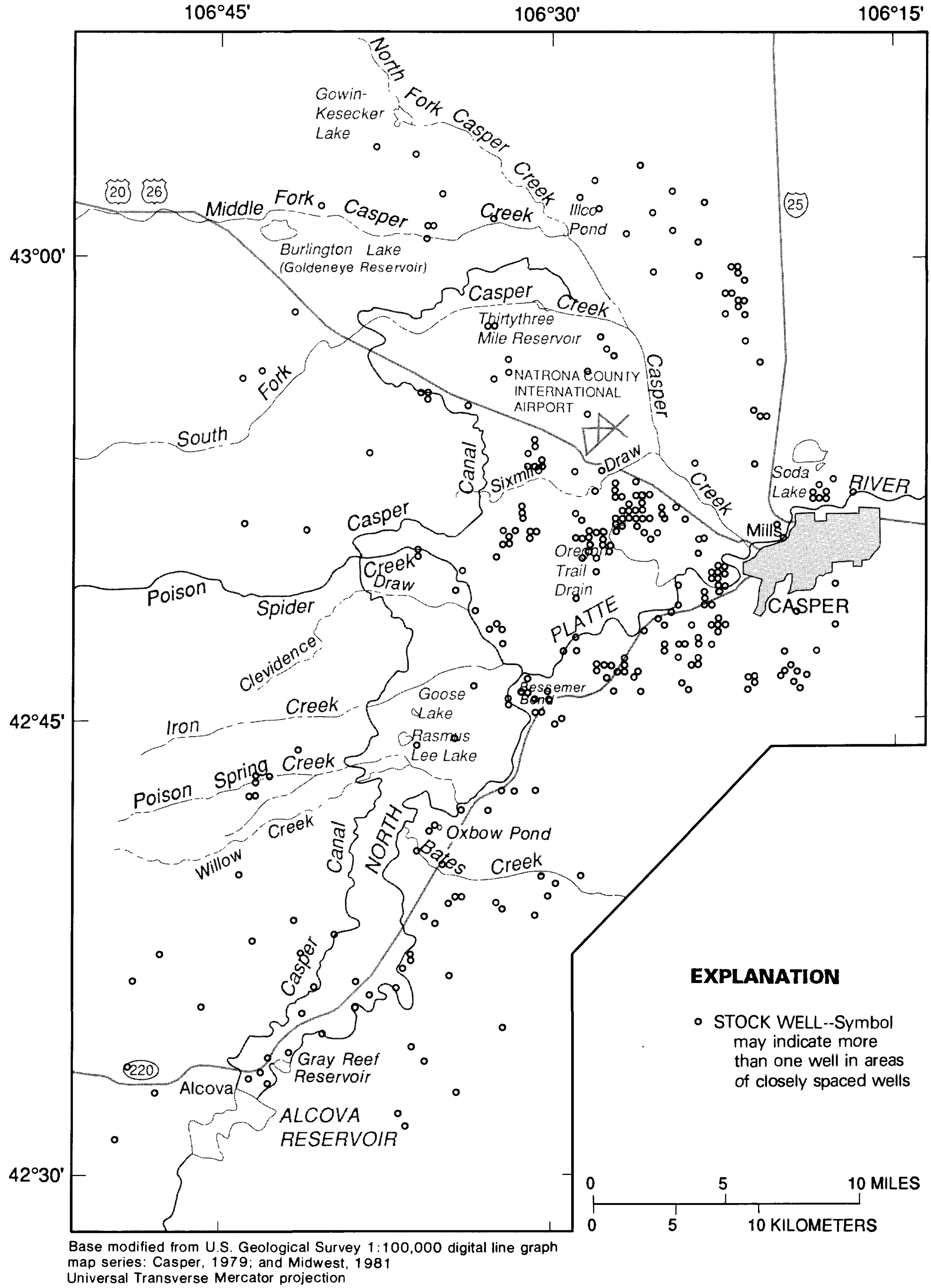
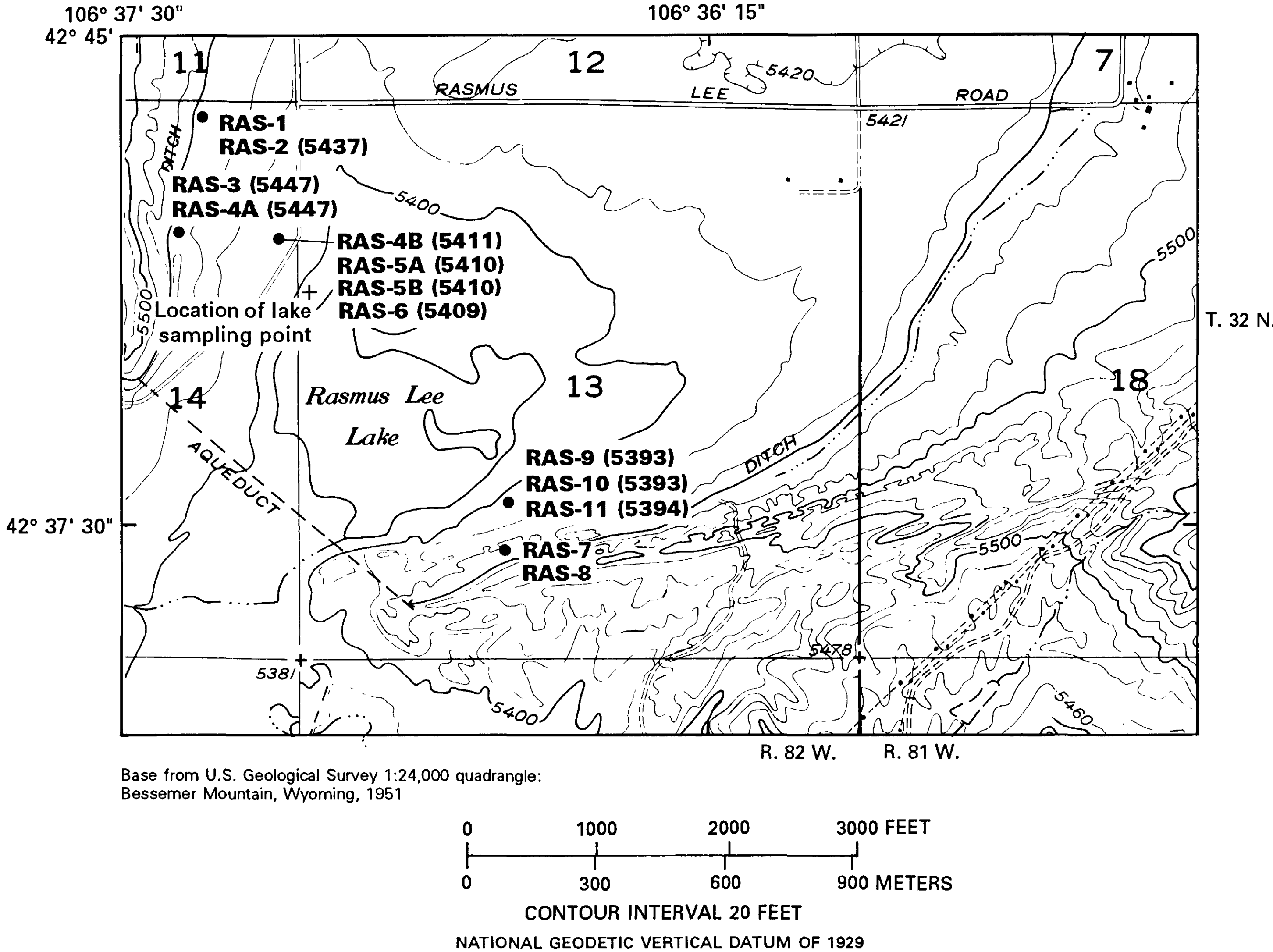


Figure 24.--Location of stock-use wells identified from the Wyoming State Engineer well-permit files during 1988. (Location plotted to the nearest quarter section.)



EXPLANATION

● **RAS-7** **RAS-8** LOCATION OF TWO OR MORE WELLS AND WELL NUMBERS
Numbers in parentheses are ground-water elevations measured in September, 1989.

Figure 25.--Location of shallow wells near Rasmus Lee Lake and lake sampling point. (Well numbers refer to table 11.)

Table 11.--Summary of data from wells near Rasmus Lee Lake

[Water levels measured and water samples collected October 19-22, 1989; µg/L, micrograms per liter; --, no data unavailable; <, less than; >, greater than]

Well number	Elevation (feet above mean sea level) Land surface	Ground water	Date measured	Depth of well (feet below land surface)	Water level (feet below land surface)	Dissolved selenium (µg/L)	Depth of perforated interval (feet below land surface)[1]	Dominant lithology of perforated interval
RAS-1	5,453	--	9-21-89	8.0	Dry	--	3.0-8.0	Shale
RAS-2	5,453	5,437	9-21-89	22.5	16.4	2,600	17.5-22.5	Sand
RAS-3	5,450	5,447	9-20-89	24.5	3.40	5	19.5-24.5	Shale
RAS-4A	5,450	5,447	9-21-89	14.5	3.46	<1	9.5-14.5	--
RAS-4B	5,411	5,411	9-20-89	33.5	Flowing[2]	14,000	28.5-33.5	Shale
RAS-5A	5,411	5,410	9-20-89	23.5	1.5	23,000	18.5-23.5	--
RAS-5B	5,411	5,410	9-20-89	23.5	.60	20,000	18.5-23.5	--
RAS-6	5,411	5,409	9-19-89	9.0	1.70	14,000	4.0-9.0	--
RAS-7	5,440	--	9-19-89	9.0	--	260	4.0-9.0	Shale
RAS-8	5,440	--	9-19-89	5.0	--	--	0-5.0	--
RAS-9	5,400	5,393	9-19-89	33.5	7.35	35	26.1-31.0	Shale[3]
RAS-10	5,400	5,393	9-19-89	22.1	6.92	51	16.5-21.5	--
RAS-11	5,400	5,394	9-19-89	9.0	6.35	--	4.0-9.0	--

[1]Wells were sealed with bentonite betwenn the casing and the well hole above the perforated interval.
[2]Well RAS-4B was capped to avoid surface contamination by ground water with large selenium concentration.
[3]Sand layer at 28.5 to 29.0 feet.

Wells RAS-7 and RAS-8 were shallow wells completed near an unlined irrigation ditch. Selenium concentration in a water sample from well RAS-7 was 260 µg/L, indicating enrichment beyond what would be expected from irrigation water.

Wells RAS-9, RAS-10, and RAS-11 were completed near the edge of Rasmus Lee Lake. Water levels in these wells were near the elevation of Rasmus Lee Lake, indicating a hydraulic connection to the lake. Selenium concentrations were 35 µg/L in a water sample from well RAS-9 and 51 µg/L in a water sample from well RAS-10. The median selenium concentration determined for water samples collected from Rasmus Lee Lake was about 40 µg/L. Similar selenium concentrations in water samples from wells RAS-9 and RAS-10, and from Rasmus Lee Lake also indicate a hydraulic connection between these wells and the lake.

Selenium and chloride concentrations (discussed in the following Geochemical Processes section of this report) were similar for Rasmus Lee Lake and wells RAS-3, RAS-4A, RAS-9, and RAS-10, which indicates similar geochemical control processes for Rasmus Lee Lake and these samples of ground water (fig. 26). Water from wells RAS-2, RAS-4B, RAS-5, RAS-6, and RAS-7 had selenium to chloride ratios that were much larger than ratios for Rasmus Lee Lake. If water from wells RAS-2, RAS-4B, RAS-5, RAS-6, and RAS-7 were in hydrologic connection to Rasmus Lee Lake, an increase in the selenium to chloride ratio would be expected for samples from Rasmus Lee Lake.

The data from the shallow wells near Rasmus Lee Lake indicate that there is large spatial variability in selenium concentrations over relatively short horizontal and vertical distances. Processes that might control the selenium concentrations are discussed in the Geochemical Processes section of this report.

On the basis of preliminary results, the potential exists for ground-water transport of selenium to Rasmus Lee Lake. Irrigation ditches to the northwest and southeast are within 0.2 mi of the lake. The water level was greater in monitoring wells adjacent to the ditches than in wells closer to the lake, indicating the potential for ground-water flow to the lake. Additionally, ground water from one of the wells in the study area contained 23,000 μg/L of selenium. If the shallow ground water and the lake are hydraulically connected, the selenium concentrations in ground water could affect lake-water quality. The existing ground-water data from the area around Rasmus Lee Lake could be analyzed further by:

1. Constructing a potentiometric-surface map and corresponding flow net to estimate the ground-water flow direction and magnitude near the lake;

2. Evaluating the potential selenium contribution to the lake with an appropriate solute-transport model and comparing the results with selenium concentrations in lake-water samples (a simple, advective analytical technique, based on flow-net analysis, could be used; alternatively, a numerical approach could be used); and

3. Evaluating the potential for vertical flow of ground water from deeper, confined aquifers to the lake, as opposed to flow of water from the lake to ground water (comparing hydraulic heads in wells completed in the aquifers).

Geochemical Processes

The geochemical cycling of selenium determines, to a large extent, the selenium concentrations in aquatic systems. The process of evaporation and the effects of natural runoff on selenium concentrations were evaluated for the Kendrick area. The processes by which selenium moves through aquatic systems might affect populations of fish and aquatic birds.

Evaporation

Because of the semiarid climate present in the study area, evaporation is a process that could affect selenium concentrations in the wetlands and shallow ground-water systems. In arid and semiarid climates, evaporation is a major control on water composition (Drever, 1988). Deverel and Fujii (1988) have shown that evaporative concentration was a major process controlling selenium concentrations in ground water beneath irrigated fields in the San Joaquin Valley of California.

Because chloride behaves conservatively in water within the study area, a plot of selenium and chloride concentrations in surface-water, ground-water, and soil-pore water samples was used to evaluate the significance of evaporation in controlling selenium concentrations. The evaporative-concentration line shown in figure 26 was derived by converting the mean concentration of selenium (1 μg/L) and chloride (8.5 mg/L) in water samples from the Casper Canal to log micromoles and log millimoles per liter and projecting along a line of unit slope. The reference monitoring sites, including Oxbow Pond and Goldeneye Reservoir, show no enrichment of selenium along the evaporative-concentration line.

Selenium and chloride concentrations in water samples from Rasmus Lee and Goose Lakes plot near the evaporative-concentration line. This plot indicates that the large and potentially toxic selenium concentrations present in water samples from both Rasmus Lee and Goose Lakes could occur by natural evaporation of water from the Casper Canal, without leaching of soluble forms of selenium from soil or rocks during irrigation in fields adjacent to these wetlands. During this study, Rasmus Lee and Goose Lakes effectively were closed basins and no surface water flowed from either basin. Surface-water and ground-water irrigation return flow from irrigated fields adjacent to Rasmus Lee and Goose Lakes were the only known sources of water to the lakes.

Concentrations of selenium and chloride in water samples from Rasmus Lee and Goose Lakes plot above the evaporative-concentration line (fig. 26) during the early part of the irrigation season, indicating leaching of soluble selenium minerals from irrigated soil in the area surrounding the lakes. Concentrations of selenium and chloride in water samples from Rasmus Lee Lake that plot below the evaporative-concentration line indicate a potential selenium sink in the lake. The concentrations of selenium and chloride in three samples that are plotted the farthest below the evaporative-concentration line were collected when the lake was ice covered, and probably reflect low redox conditions. Under low redox conditions, the more reduced forms of selenium (Se^{-2}, Se^{0}, Se^{+2}, and Se^{+4}) are more stable than the most oxidized form of selenium (Se^{+6}) and are more readily adsorbed or precipitated in mineral forms (McNeal and Balistrieri, 1989).

Concentrations of selenium and chloride in water samples from two wetlands, Thirtythree Mile Reservoir and Illco Pond, shallow ground water, and soil-pore water indicate considerable enrichment in selenium compared to concentrations approximated by the evaporative-concentration line (fig. 26). Thirythree Mile Reservoir and Illco Pond are flow-through systems and receive surface-water inflow from larger drainage basins than do Rasmus Lee and Goose Lakes. Concentrations of selenium and chloride in some shallow ground-water samples and soil-pore-water samples from areas near Rasmus Lee Lake indicate considerable enrichment compared to concentrations approximated by the evaporative-concentration line.

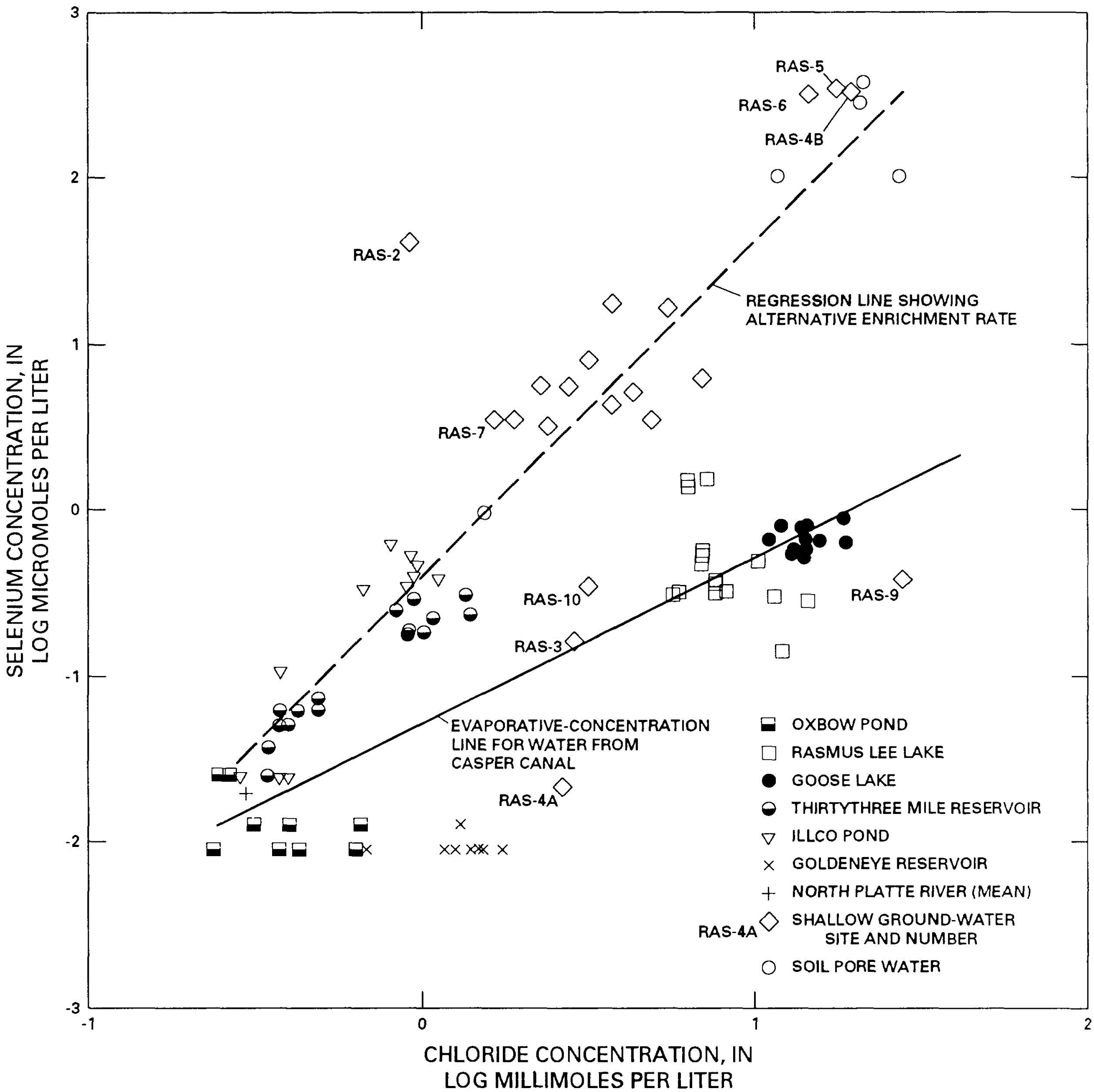


Figure 26.--Selenium and chloride concentrations in surface-water, ground-water, and soil-pore water samples in relation to selenium and chloride concentrations approximated by evaporation of irrigation water before field application.

The enrichment of selenium above the evaporative-concentration line for the surface-water samples from Thirtythree Mile Reservoir, Illco Pond, shallow ground water, and soil-pore water indicates a selenium source in addition to irrigation water affected by evaporative concentration. The probable sources for the additional selenium are leaching and desorption of soluble forms of selenium from soil and rocks exposed to ground and surface water in the study area. Large selenium concentrations in soil and plant samples were identified in the northern part of the Kendrick area.

Unlike the water from Rasmus Lee and Goose Lakes, samples of irrigation drainwater from the Casper Canal in the Kendrick area plot above the selenium and chloride evaporative-concentration line (fig. 27). This enrichment of selenium above the evaporative-concentration line indicates that a substantial part of the selenium concentrations detected in the irrigation drainwater samples is derived by leaching or desorption of soluble forms of selenium from soil and rocks during irrigation.

To further investigate evaporative processes in the water in the Kendrick area, O-18/O-16 and D/H isotopic ratios were determined in selected surface- and ground-water samples (fig. 28). The isotopic composition of selected surface-water samples is shifted to the right of the North American continental precipitation line ($y = 8x + 6$) (Gat, 1980), indicating various degrees of evaporation. The best-fit line through the isotopic data follows a trend line defined by the equation $y = 5.3x - 40.3$ (fig. 28). A slope less than the continental precipitation line is characteristic of evaporation. In agreement with the selenium/chloride ratios, water samples from Rasmus Lee and Goose Lakes have the heaviest isotopic values, verifying the substantial effect evaporation has on the selenium concentrations at these sites.

The isotopic composition of water samples from the shallow ground water in the Kendrick area, Thirtythree Mile Reservoir, and Illco Pond plots close to the North American continental precipitation line, indicating limited evaporative-concentration effects (fig. 28). The isotopic composition of the shallow ground water is similar to the isotopic composition of irrigation water from Casper Canal, suggesting a localized, surface-water recharge source. The isotopic composition of water samples from the shallow ground water, from Thirtythree Mile Reservoir, and from Illco Pond (fig. 28) combined with their enriched selenium/chloride ratios (fig. 26) both indicate limited evaporative concentrations of selenium and substantial leaching and desorption of soluble forms of selenium from soil and rocks in the Kendrick area.

Natural Runoff

Through transpiration and evaporation of irrigation water, salts originally dissolved in water are left behind. These mineral salts remain in the soil and can accumulate as deposits on the soil surface unless sufficient quantities of water are available to leach out the salts and move them out of the soil profile. Natural runoff from snowmelt or rainstorms might dissolve surficial salt deposits and flush the salts into nearby water resources.

The water quality of Rasmus Lee Lake was monitored during March and April of 1988 and 1989 because of potential increases in selenium concentrations from dissolution of salts by natural runoff. The location of the sampling point on Rasmus Lee Lake is shown on figure 25. Also in March, migratory aquatic birds begin to use wetlands in the Kendrick area as stop-over habitats.

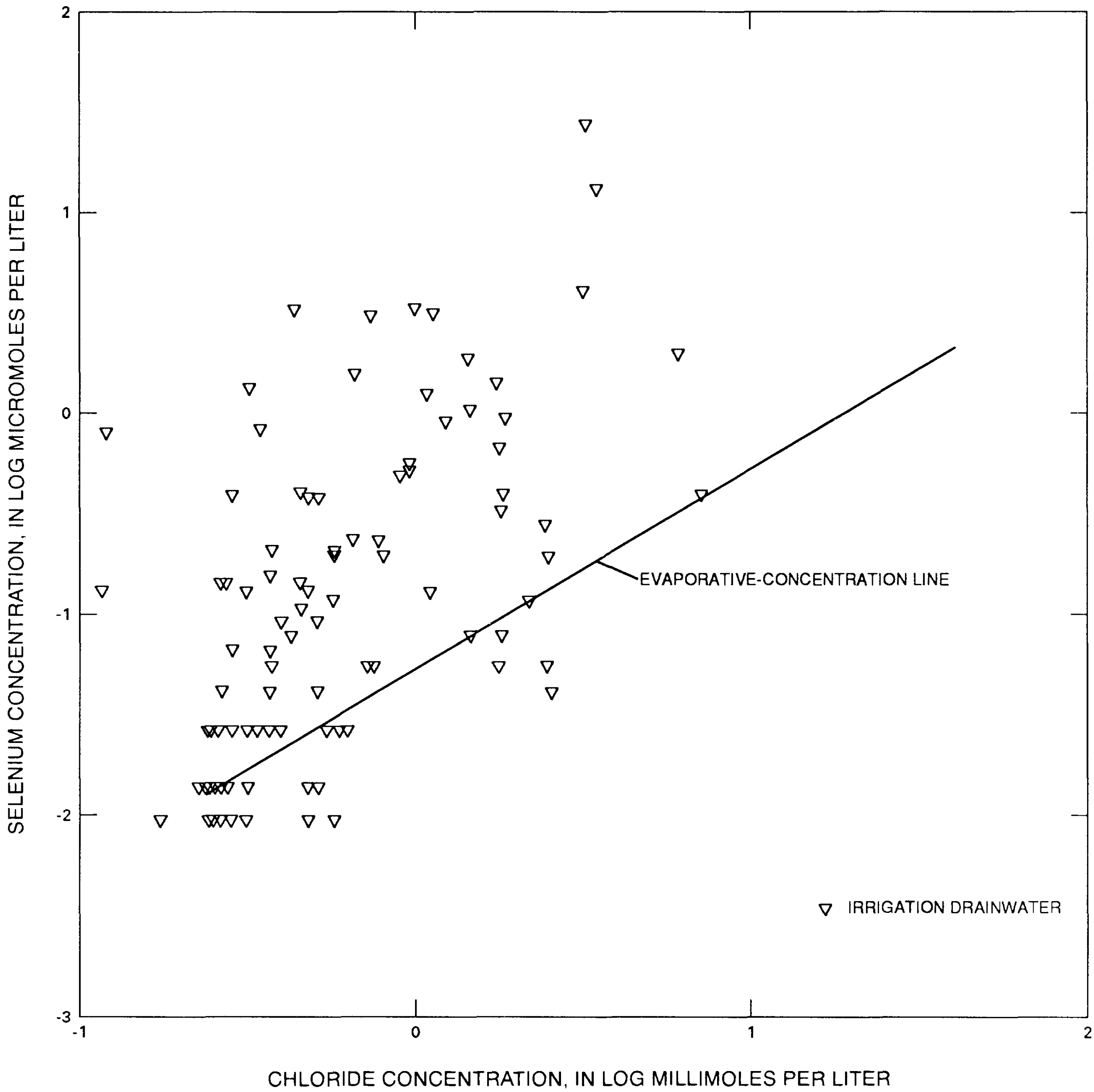


Figure 27.--Relation of selenium and chloride concentrations in irrigation-drainwater samples to selenium and chloride concentrations estimated by evaporation of irrigation water before field application.

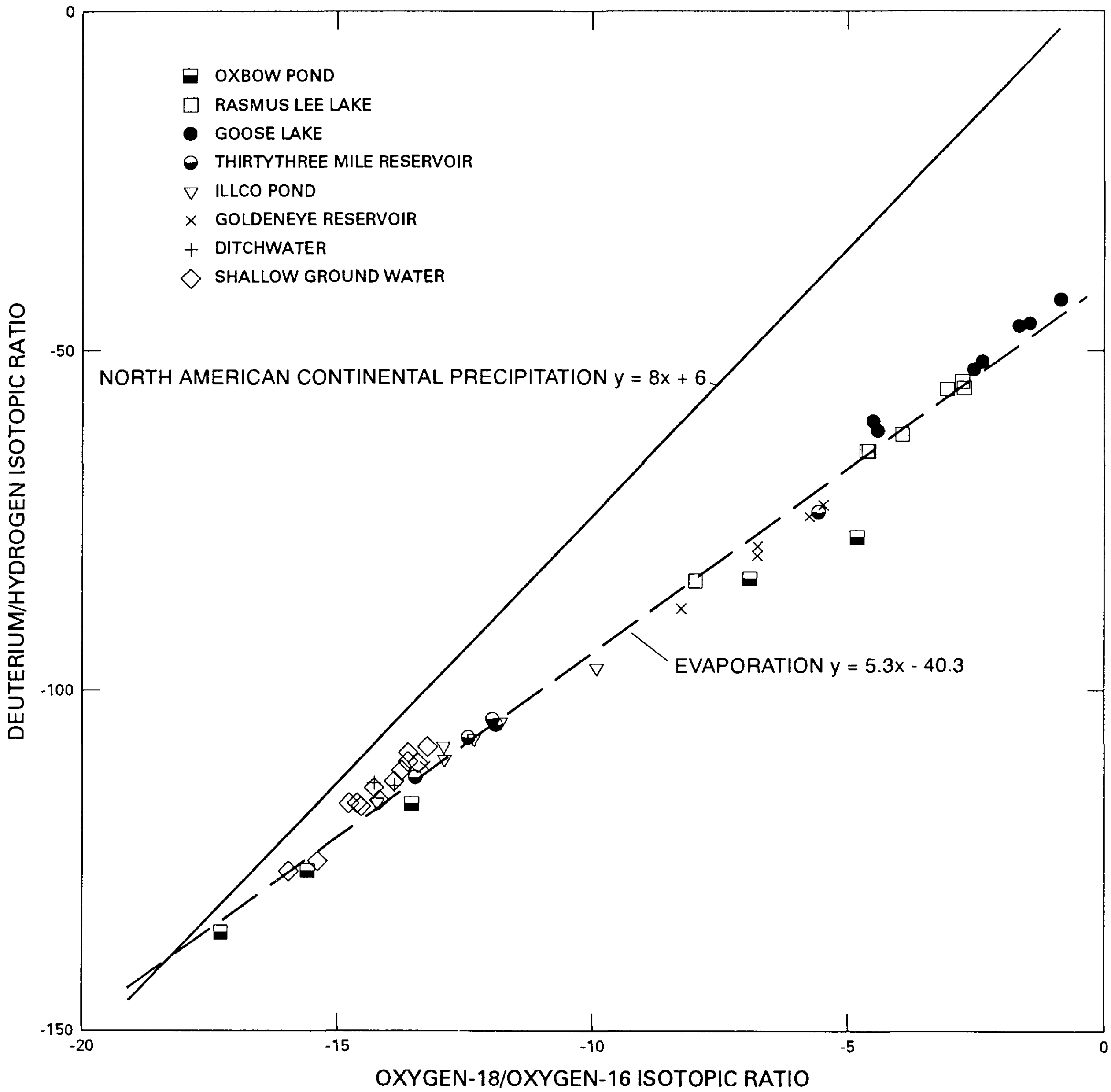


Figure 28.--Relation of deuterium/hydrogen and oxygen-18/oxygen-16 isotopic ratios in surface- and ground-water samples to the North American continental precipitation line.

Water samples were collected daily from a depth of about 1 ft below the water surface in Rasmus Lee Lake using an automatic pumping sampler. Each sample was analyzed for total (dissolved plus suspended) selenium and specific conductance. Turbidity also was determined in water samples collected during 1989.

Results obtained during 1988 show a large increase in total selenium concentration after a large natural runoff of snowmelt beginning on March 17 (fig. 29). Snowdepth was measured at Natrona County Airport. During this snowmelt, total selenium concentrations increased from less than 50 μg/L measured on March 18 to about 1,300 μg/L measured on March 22. The peak selenium concentration during this period also was accompanied by the partial removal of ice from the lake surface and a decrease in specific conductance from about 14,000 μS/cm to about 5,000 μS/cm (fig. 29).

The increase in selenium concentration combined with the decrease in specific conductance could be caused by a variety of factors including: (1) turbulence affecting bottom sediment; (2) a change in the redox state of the water from ice covered (reducing conditions) to ice break-up (oxidizing conditions); and (3) dissolution of selenium-rich salts near the lake accompanied by decreases in specific conductance caused by the melting of the lake ice. Bottom sediment from Rasmus Lee Lake contains large selenium concentrations (25 μg/g). The gentle topography surrounding Rasmus Lee Lake would not provide turbulent flows during snowmelt; however, wind might play a role in mixing the water and bottom sediment, because of the shallow depth of the lake.

Removal of ice cover from Rasmus Lee Lake has a large effect on the redox state of the water. During 1989, under ice-covered conditions, water from Rasmus Lee Lake had a dissolved-oxygen concentration of 0.35 mg/L and a strong smell of hydrogen sulfide, which is indicative of reducing conditions. After removal of ice, the dissolved-oxygen concentrations increased to as much as 20 mg/L. During ice removal, it is possible that the change in redox conditions from reducing to oxidizing caused some of the reduced forms of selenium to be oxidized to selenium^{+6} and desorbed from the bottom sediment.

Snowmelt runoff to Rasmus Lee Lake, concurrent with the melting of ice cover, could diminish the large specific conductance signature expected from dissolution of selenium-bearing salt crusts on the shore of Rasmus Lee Lake. Specific conductance of ice samples collected from Rasmus Lee Lake in February 1989 averaged 4,300 μS/cm compared to a specific conductance of 19,000 μS/cm measured in water samples from below the ice. A salt-crust sample collected from the shore of Rasmus Lee Lake in 1988 contained a total selenium concentration of 70 μg/g.

During a snowmelt beginning on April 23, 1988, when Rasmus Lee Lake was ice-free, total selenium concentrations and specific conductance increased (fig. 29). The concurrent increase in total selenium concentration and specific conductance indicates dissolution of selenium-bearing salt crusts that had accumulated on the lake shore since the last snowmelt. The April 23, 1988, snowmelt was preceded by the large snowmelt on March 17 through March 23 followed by about 4 weeks of dry weather with only trace amounts of precipitation. This wet/dry cycle could enhance the weathering of seleniferous soil and the formation of selenium-bearing salt crusts during this time period.

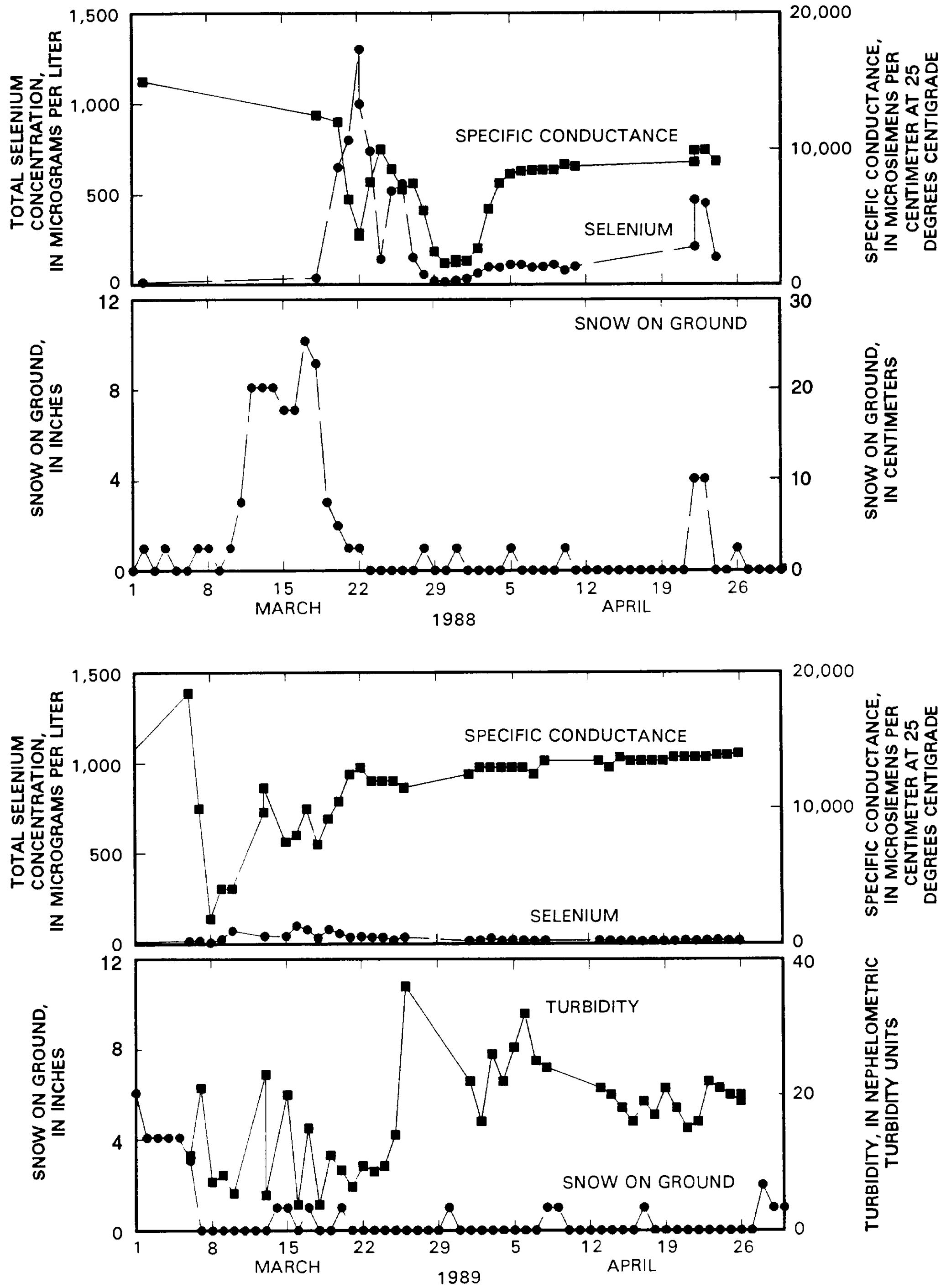


Figure 29.--Temporal variations in depth of snow near Rasmus Lee Lake and in total-selenium concentrations, specific conductance, and turbidity in water samples from Rasmus Lee Lake during March and April, 1988 and 1989. (Snowdepth as measured at Natrona County International Airport.)

Total selenium concentrations in Rasmus Lee Lake did not exceed 100 μg/L from March through April 1989 and did not show a correlation with snowmelt, specific conductance, or turbidity (fig. 29). Comparison of the 1988 and 1989 data shows the large monthly and yearly variations of selenium concentrations that can occur at wetlands.

Increased selenium concentrations at Rasmus Lee Lake and other wetlands in the Kendrick area during late winter and early spring snowmelt is important because of the increased bird use observed during this time period. The large selenium concentrations in water from Rasmus Lee Lake during March and April 1988 coincide with increased migratory aquatic bird and shorebird use during the spring migration. The increased selenium concentrations in the water during this time period might increase the availability of selenium in the food chain. Aquatic birds and shorebirds stopping at Rasmus Lee Lake during migration might accumulate enough selenium to cause adverse reproductive effects.

For example, onsite studies at the Ouray National Wildlife Refuge (Ouray) in Utah demonstrated significant selenium accumulation in 1 week by captive-raised mallards (Anas platyrhynchos) released into a pond with large concentrations of selenium in the food chain (Bruce Waddell, U.S. Fish and Wildlife Service, Salt Lake City, UT, oral commun., 1990). Waddell determined that the mean selenium concentrations in mallard livers increased from 2.8 to 27 μg/g dry weight. The liver of a mallard that survived for 4 weeks at the pond contained a selenium concentration of 106 μg/g. None of the 44 captive mallards released at the contaminated pond survived longer than 4 weeks.

BIOTA

Concentrations of trace elements in biota were investigated to determine concentrations in the food chain and to determine the major pathways for selenium to higher trophic levels such as fish and birds. Several streams and a drain convey irrigation drainwater from the Kendrick area to the North Platte River and contribute to selenium bioaccumulation in the trout fishery at concentrations suspected of adversely affecting reproduction.

Fish Resources

The North Platte River from Alcova Reservoir downstream to the Bessemer Bend area is a blue-ribbon trout fishery and forms a large part of the Kendrick area boundary to the south and east. Poison Spider, Poison Spring, and Casper Creeks and the Oregon Trail Drain are principal tributaries draining from the Kendrick area into the North Platte River. The reach from Bessemer Bend to Casper supports a good trout fishery and is maintained primarily through stocking efforts of the Wyoming Game and Fish Department (Bill Wichers, Wyoming Game and Fish Department, oral commun., 1989). The North Platte River from Alcova Reservoir to Casper supports a variety of fish species (Baxter and Simon, 1970). Goldeneye Reservoir, a reference site 5 miles west of the Kendrick area, supports cutthroat trout, carp, and white suckers. The reservoir is managed by the U.S. Bureau of Land Management as a recreational area.

No other important stream or lake fisheries exist in the study area. Fish were virtually nonexistent at Rasmus Lee Lake where only one plains killifish (*Fundulus kansae*) was collected during the course of this study, and fish were absent from Goose Lake. Thirtythree Mile Reservoir supports carp (*Cyprinus carpio*), black bullhead (*Ictalurus melas*), and green sunfish (*Lepomis cyanellus*). Trout are not stocked at Thirtythree Mile Reservoir because the impoundment is not deep enough to support this species during the winter (Bill Wichers, Wyoming Game and Fish Department, oral commun., 1990). Thirtythree Mile Reservoir is fished one or two days per year, primarily by farm workers (Bob Bressler, land owner, Casper, Wyoming, oral commun., 1990). Illco Pond supports carp and brassy minnows (*Hybognathus hankinsoni*).

Aquatic Bird Resources

The Kendrick area is along the Central Flyway, although migratory birds from the Pacific Flyway might fly to and from the study area. Prior to this study, aquatic bird use of wetlands in the Kendrick area was not well documented. Although the Wyoming Game and Fish Department conducted annual aerial aquatic bird surveys on portions of the study area adjacent to the North Platte River, species diversity as well as duration and variability of use were unknown.

Some aquatic birds are hunted in the Kendrick area. Goose Lake and Thirtythree Mile Reservoir are leased for duck and goose hunting by landowners. Goose Lake was not leased to aquatic bird hunters in 1989; however, in previous years it was leased to two people who hunted the lake about six times during the season (Mrs. John Milne, landowner, Casper, Wyoming, oral commun., 1990). Thirtythree Mile Reservoir has been leased to five or six local individuals (Bob Bressler, landowner, Casper, Wyoming, oral commun., 1990). Evidence of hunting was observed at Rasmus Lee Lake; however, the actual amount of hunting and harvest is unknown.

Sample Collection and Analytical Methods

Aquatic bird use in the study area was quantified by a weekly census from March through October in 1988 and 1989. Bird surveys were conducted at Rasmus Lee and Goose Lakes, Illco and Oxbow Ponds, and Thirtythree Mile Reservoir. Access to Illco Pond was not permitted in 1989; hence, no data are available for that year. Observations were made using a 15- to 60-power zoom-spotting scope and binoculars. Counts were made between 0700 and 1100 hours. Date, time of survey, duration of survey, species, and total number of individuals per species were recorded.

Biological samples were collected by the U.S. Fish and Wildlife Service with assistance from the Wyoming Game and Fish Department. Aquatic invertebrates were collected at Rasmus Lee and Goose Lakes, Illco and Oxbow Ponds, and Thirtythree Mile Reservoir with light traps similar to those described by Espinosa and Clark (1972). All aquatic invertebrate collections were made in water depths less than 4 ft. Benthic invertebrates (Chironomid larvae) were picked from bottom grab samples and from the surface with a sweep net at Rasmus Lee Lake and Oxbow Pond. Submerged aquatic vegetation was collected manually from Rasmus Lee and Goose Lakes, Illco and Oxbow Ponds, Thirtythree Mile Reservoir, and Soda Lake, a reference site north of Casper. Fish were collected from Illco Pond, Thirtythree Mile and Goldeneye Reservoirs, and several reaches of the North Platte River using electroshocking equipment, seines, and gill nets. Whole fish samples collected at Illco Pond, Thirtythree Mile and Goldeneye Reservoirs were analyzed. Muscle tissue from fish collected at the North Platte River and Goldeneye Reservoir were analyzed.

Adult and juvenile aquatic birds were collected for liver samples using a shot gun and steel shot. Aquatic bird carcasses found in the study area were retrieved and submitted for necropsy to the Colorado State University Veterinary Diagnostic Laboratory at Fort Collins, Colorado. Bird livers and breast muscle tissue were removed from bird specimens with stainless steel dissection tools and placed in pre-cleansed (acid washed and solvent rinsed) glass jars for tissue residue analyses. All biological specimens were kept on ice and then frozen as soon as possible.

Biological samples were analyzed for trace elements by the following laboratories under contract with the U.S. Fish and Wildlife Service Patuxent Analytical Control Facility (PACF): Hazelton Laboratories America, Inc., Madison, Wisconsin; Environmental Trace Substances Research Center, Columbia, Missouri; and Research Triangle Institute, Research Triangle Park, North Carolina. The laboratories analyzed the samples for selenium and arsenic using hydride generation atomic absorption spectroscopy (HGAAS) or graphite furnace atomic absorption spectroscopy (GFAAS) and for mercury by cold vapor reduction (CV). Boron, cadmium, and lead were analyzed by inductively coupled plasma atomic spectroscopy (ICP). Organochlorine pesticides and polychlorinated biphenyls (PCBs) were analyzed by organochlorine scan using packed, capillary, or megabore column, electron capture gas chromatography. Laboratory quality control was assured through the PACF. The precision and accuracy of the laboratory analyses were confirmed with procedural blanks, duplicate analyses, test recoveries of spiked materials, and reference material analyses. All U.S. Fish and Wildlife Service analyses received a PACF quality-assurance review.

The primary method used to assess accuracy was percentage recovery of spiked analyte. Laboratory accuracy was established for each type of analysis and was expected to be within the standards listed in table 12. Duplicate samples were analyzed to provide a measure of analytical precision. Duplicate analyses were evaluated in accordance with the criteria listed in table 13.

Table 12.--Standards of accuracy for trace residue analyses

[ICP, inductively coupled plasma spectroscopy; AA, atomic absorption spectroscopy; GC, gas chromatography]

Method	Analyte	Acceptable recovery range of spiked analyte (percent)
ICP	Boron	80-120
	Cadmium	80-120
	Lead	80-120
AA	Selenium	85-115
	Arsenic	85-115
GC	Organochlorine pesticides	80-120

The test recoveries of spiked materials reported with a batch of samples submitted to a laboratory for analyses were compared to the average recovery for that laboratory and each analyte. If the reported recoveries were within the 95-percent confidence interval for the mean recovery, the accuracy of the analysis was considered acceptable by PACF. In addition to the test recoveries of spiked materials, standard reference materials were analyzed. Results were compared to both the laboratory average and the certified value. Accuracy and precision for biota sample analyses included in this report were considered acceptable by PACF.

Percentage moisture and dry-weight concentrations were reported by the laboratories. Wet-weight concentrations were calculated by multiplying the dry-weight concentrations times the factor (one minus the percent sample moisture expressed as a decimal). Wet-weight reporting limits were calculated in the same way. Analyte geometric mean concentrations and standard errors were calculated for each sample type for each location (if there were five or

Table 13.--Criteria for laboratory analyses of duplicate samples

[ICP, inductively coupled plasma spectroscopy; AA, atomic absorption spectroscopy; LOD, limit of detection; >, greater than; John Moore, Patuxent Analytical Control Facility Reference Manual, written commun., 1990]

Analyte	Concentration range[1]	± 95 percent confidence interval	Average relative percentage difference[2]
Metals (ICP)[3]	2-10 x LOD	30	17.3
Metals (ICP)[3]	> 10 x LOD	15	8.64
Metals (AA)[4]	2-10 x LOD	20	11.5
Metals (AA)[4]	> 10 x LOD	10	5.75
Organochlorine pesticides	2-10 x LOD	30	17.3
Organochlorine pesticides	> 10 x LOD	15	8.64

[1]The range, in multiples of the limit of detection, in which the sample falls. For samples with a concentration less than two times the limit of detection, the 95 percent confidence interval is assumed to be ± 2 x LOD.

[2]The relative percentage difference needed to produce the stated 95 percent confidence level listed in the table. This is the average of all the relative percentage differences of a given laboratory in a given matrix.

[3]ICP analyses included boron, cadmium, and lead.

[4]AA analyses included selenium and arsenic.

more samples of the same type from that location). A value of one-half the reporting limit was used for calculations of means and standard errors when a sample concentration was less than the reporting limit.

The reproductive success of aquatic birds at the Kendrick area was monitored between April and August in 1988 and 1989. Nesting birds that were monitored comprised Canada geese, American avocets, and eared grebes. Nest monitoring effort is presented in detail in table 14.

Nesting success was calculated by dividing the number of nests presumed to have hatched at least one egg by the total number of nests monitored (Klett and Johnson, 1982, p. 77). Hatching success of eggs was calculated by dividing the total number of eggs presumed to have hatched by the total number of eggs found in monitored nests. Egg hatchability, the ratio of eggs presumed

Table 14.--Frequency of aquatic bird nest monitoring in the Kendrick area and at Illco Pond during 1988 and 1989

Species monitored	Months of monitoring	Maximum number of nest visits	Number of days between visits
		1988	
Canada goose	May and June	6	5-8
American avocet	May, June, and July	4	7-16
Eared grebe	June and July	4	7-16
		1989	
Canada goose	May and June	5	7-15
American avocet	May, June, and July	9	1-24
Eared grebe	June and July	6	2-16

hatched to adjusted clutch size, was calculated. Egg hatchability was calculated for successful nests and for combined successful nests and nests with embryo toxicity. Nests with embryo toxicity contained one or more dead or deformed embryo(s) that persisted to predicted hatch dates (Ohlendorf and others, 1989, p. 790). Adjusted clutch sizes were determined by subtracting eggs missing prior to earliest hatching dates and the number of viable eggs that were collected. Nests that were abandoned prior to predicted hatch dates and nests with incomplete observations were excluded from the egg hatchability calculations. By adjusting clutch sizes and sample sizes in this way, all causes of egg failure other than embryo toxicosis were eliminated (Ohlendorf and others, 1989, p. 790).

Canada goose eggs were well into incubation when found, and some had hatched or failed. Therefore, the estimate of goose nesting success might be higher than actual nesting success because some failed nests might have been missed, thereby inflating the estimate. However, the possibility of missing an abandoned nest or early nest failure is reduced by the lack of nest predation. Also, many addled eggs persisted well after estimated hatch dates or abandonment. Three goose nests were visited only once in 1988, but all goose nests were monitored to hatching or failure in 1989. American avocet nests were monitored from egg laying through maximum estimated hatch dates. Observations on three avocet nests were not completed in 1988, and three avocet nests were visited only once in 1989. Eared grebe nests were monitored from egg laying through hatching or failure. In 1988, 122 grebe nests were found and 107 were monitored to hatching or failure. In 1989, a sample of only 59 grebe nests (including two renests) was monitored to maximum hatch dates to minimize observer disturbance.

Nests with incomplete observations or unknown fates (visited only once or not monitored through maximum estimated hatch dates) were excluded from calculations. Exclusion of unknown-fate nests could bias results, particularly for early layers and nests that did not persist (Klett and Johnson, 1982, p. 77; Mayfield, 1961, p. 261; Mayfield, 1975, p. 456; Miller and Johnson, 1978, p. 471).

Hatch dates were estimated by evaluating the date of initial visit, clutch size, incubation period, and incubation stage of randomly collected eggs. Eggs that disappeared during the estimated hatching period were presumed hatched unless signs of predation or strife were observed. As some egg losses could have gone undetected, hatching estimates may be inflated, particularly for grebes. Grebe nests disintegrated rapidly, but goose and avocet nests and eggs persisted after termination of nesting. In addition, only five goose and two avocet eggs that contained dead embryos were found outside of nests in 1989. However, 28 grebe eggs with dead embryos were found floating in the nesting area in 1989 but could not be attributed to specific nests. Nest and total egg hatching success estimates are inflated further because viable eggs that were collected randomly from nests early in incubation were counted as presumed hatched. At least some of these eggs probably would have died later if they were left in the nest. In contrast, egg hatchability results do not include viable eggs collected and, therefore, provide a more sensitive measure of hatching success.

Active nests were determined by egg warmth and the external condition of the nest and eggs. Specific signs used to indicate active nests were: warm eggs, goose nest covered with down, aquatic vegetation covering eared grebe nests, or grebe eggs stained evenly indicating active egg rotation by the adult. Eggs that were cold or hot, covered with dirt, or stuck to the ground or nest material were considered abandoned. If eggs were not abandoned, embryo toxicosis was the assumed cause of failure of eggs containing dead or deformed embryos (Ohlendorf and others, 1989, p. 790). Eggs that failed to hatch were collected and the embryos were examined for deformities. Embryo age was estimated during dissection by estimating the developmental stage (Caldwell and Snart, 1974, p. 298-300; Cooper and Batt, 1972, p. 1267-1269). Egg contents were placed in pre-cleansed glass jars and frozen. Egg contents were sent later to contract laboratories for tissue residue analyses.

Aquatic Bird Use

The Kendrick area serves as an important spring and fall stopover for migratory birds and also provides nesting habitat for a few species of aquatic birds, including Canada geese (*Branta canadensis*), American avocets (*Recurvirostra americana*), eared grebes (*Podiceps nigricollis*), mallards (*Anas platyrhynchos*), blue-winged teals (*Anas discors*), and gadwalls (*Anas strepera*). Peak numbers of aquatic birds were observed during late August and September (fig. 30). In general, more birds were observed in 1989 than in 1988, perhaps because of the drier conditions in 1989, which would have concentrated more birds in fewer wetlands. Species composition of aquatic birds observed using the wetlands in the Kendrick area and at Illco Pond is shown in figure 31.

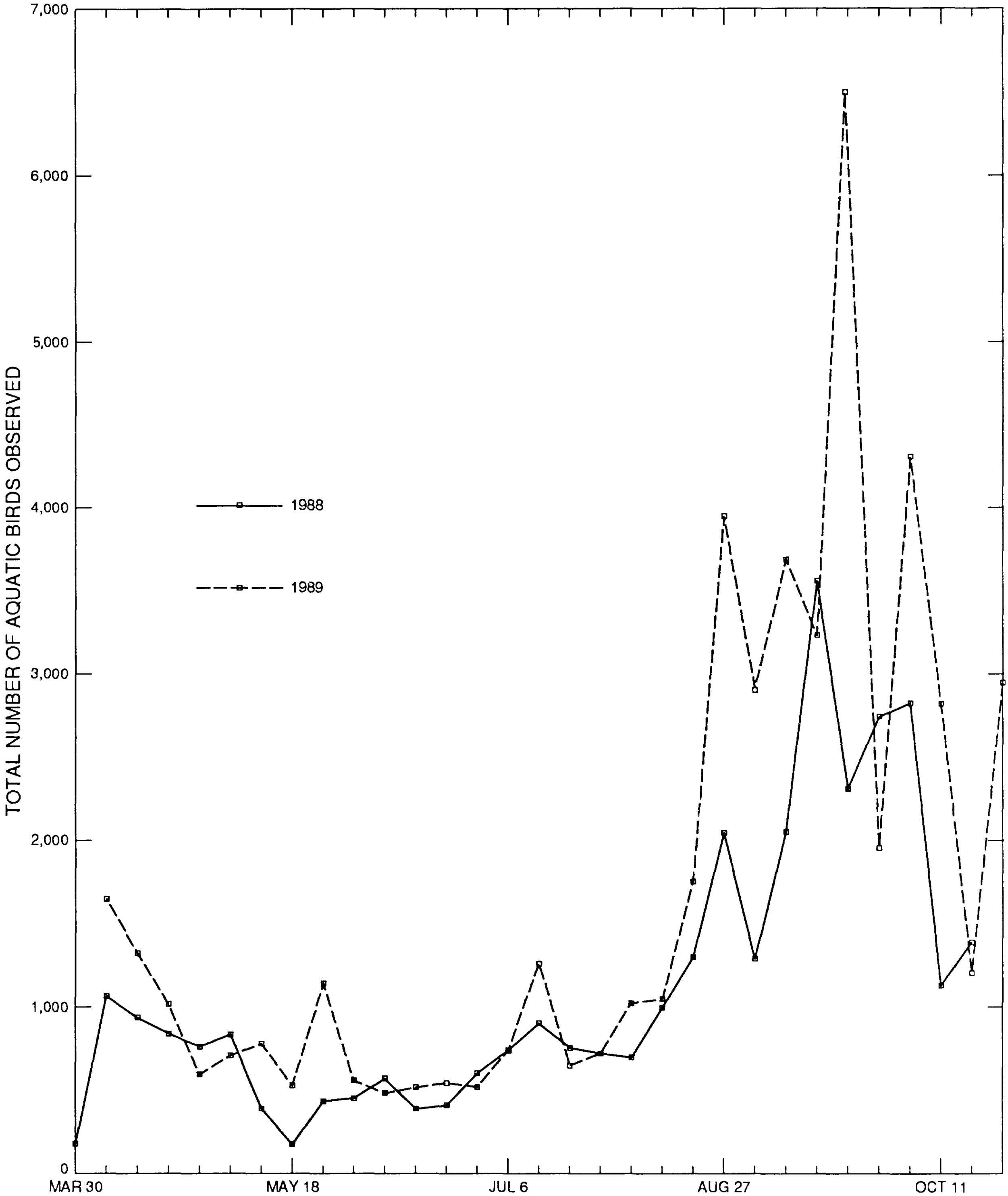


Figure 30.--Total number of aquatic birds observed in the Kendrick area and at Illco Pond during weekly surveys from March through October, 1988 and 1989.

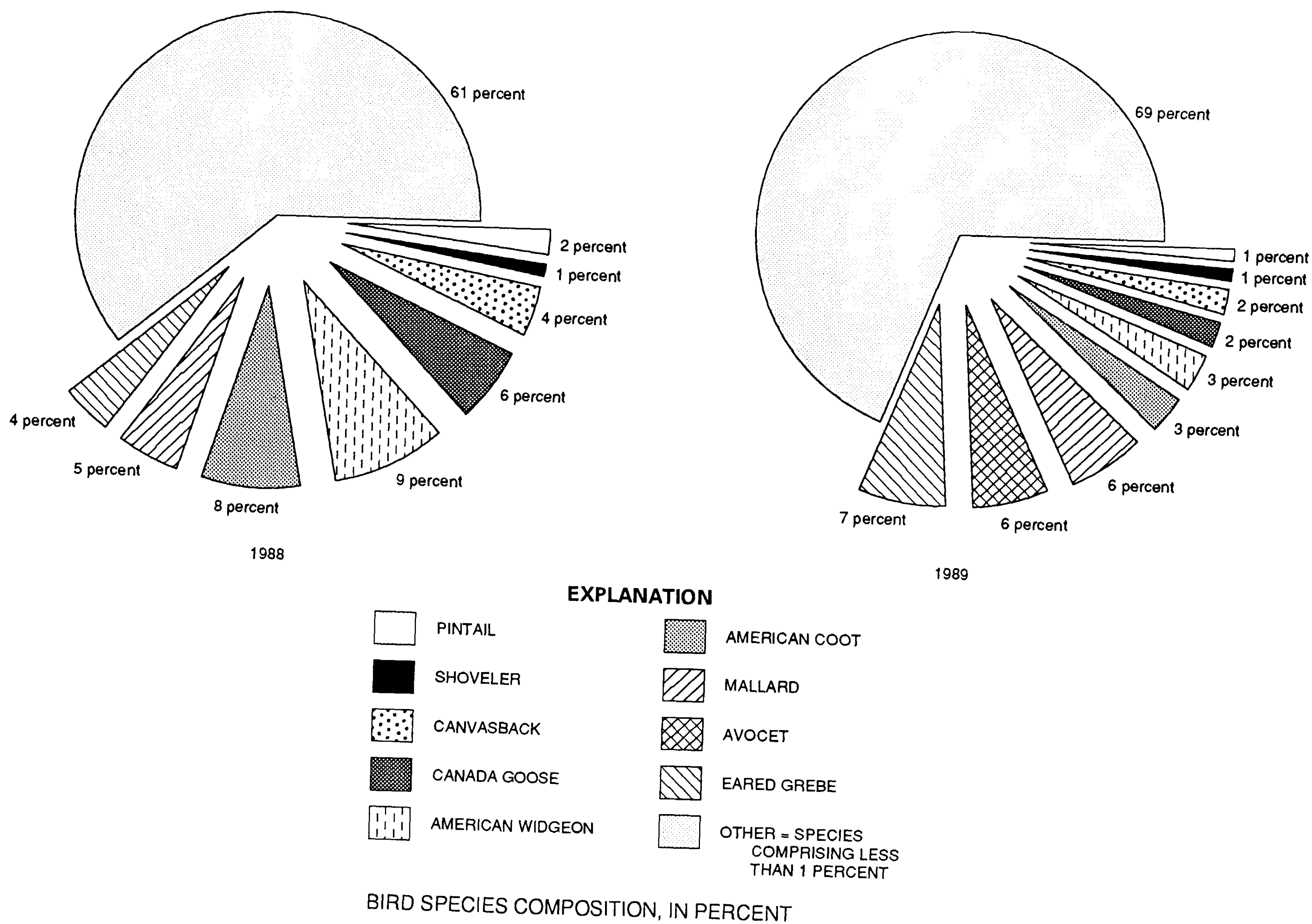


Figure 31.--Species composition of aquatic birds observed in the Kendrick area and at Illco Pond from March through October, 1988 and 1989.

Aquatic birds feed on submerged aquatic vegetation and aquatic and benthic invertebrates in wetlands in the Kendrick area. Some waterfowl species such as Canada geese and mallards were observed feeding in fields adjacent to Kendrick area wetlands.

Aquatic bird production is limited because of the scarcity and type of habitat available along the North Platte River and in the Kendrick area. A limited number of aquatic birds, primarily dabbling ducks (Anas spp.), nest along water bodies and on upland sites in the Kendrick area. Wilson's phalaropes (Phalaropus tricolor) nest in wet meadows near ponds, lakes, and drainages.

Canada geese nested on three small islands on Rasmus Lee Lake. One nest also was observed at Oxbow Pond in 1988. Canada geese might nest in other parts of the study area; however, nesting observations were limited to Rasmus Lee Lake and Oxbow Pond. Canada goose nesting extended from April through June. Broods were observed first in mid-May, and the goslings generally fledged in late July and early August. A maximum of 48 goslings were observed in 1988, and 66 were observed in 1989. During the nesting season, Canada geese were observed primarily at Rasmus Lee Lake, their principal nesting site. Total numbers of Canada geese observed during 1988 and 1989 in the Kendrick area are shown in figure 32.

American avocets arrived at the study area in mid-April and most left by mid-August. Avocets nested primarily on islands at Rasmus Lee Lake, although a few nests were observed on mud flats along the shorelines of Goose Lake and Illco Pond. Avocets nesting at Rasmus Lee Lake also appeared to use Goose Lake as a feeding area. Avocets nested from the first week of June through July. Juvenile avocets were not observed during 1988; during 1989, six were observed at Rasmus Lee Lake, and four were observed at Goose Lake. Total numbers of avocets observed during 1988 and 1989 in the Kendrick area and at Illco Pond are shown in figure 33.

Goose Lake provides nesting habitat for eared grebes. Eared grebes were first observed during the middle of April with peak numbers from June through the end of the nesting season in July. Eared grebes nested on floating platforms made of sago pondweed (Potamogeton vaginatus) anchored to bulrush (Scirpus spp.) stands in Goose Lake. Nesting occurred from late June to mid-July and broods first were observed in mid-July. Ten juvenile eared grebes were observed in 1988, and 77 were observed in 1989. Total numbers of eared grebes observed at Rasmus Lee and Goose Lakes and Thirtythree Mile Reservoir during 1988 and 1989 are shown in figure 34. Eared grebes were not observed at Illco and Oxbow Ponds.

Aquatic bird species observed in the Kendrick area are listed in table 15. Observations of uncommon birds included a trumpeter swan (Cygnus buccinator) at Rasmus Lee Lake and a Eurasian widgeon (Anas penelope) at Goose Lake during April 1989. Canvasbacks (Aytha valisineria), a declining species, were commonly observed at Rasmus Lee and Goose Lakes (fig. 35).

Bird banding recovery data for the study area are limited. Most Canada geese recovered with bands near the study area were banded in Wyoming. Mallards recovered with bands near the Kendrick area were banded in Colorado and Canada.

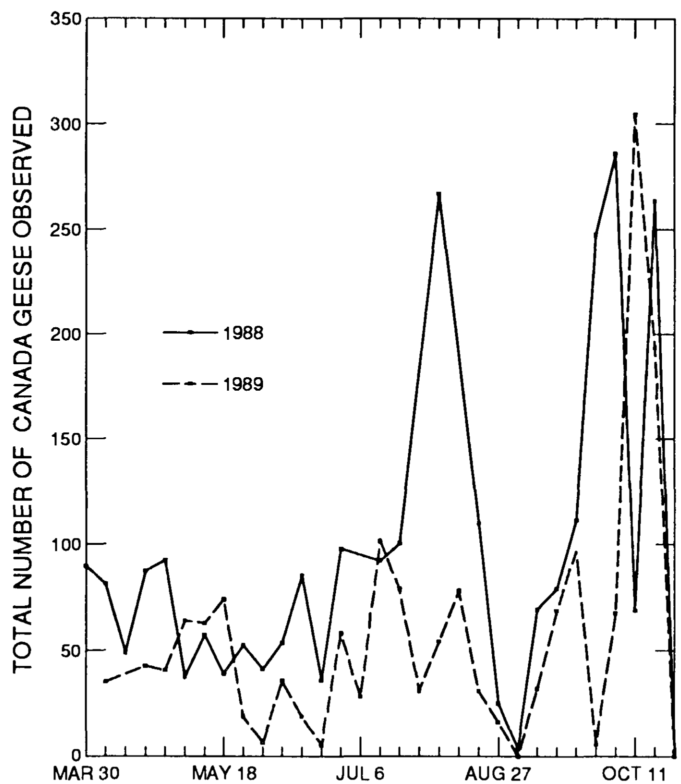


Figure 32.--Total number of Canada geese observed in the Kendrick area and at Illco Pond during weekly surveys from March through October, 1988 and 1989.

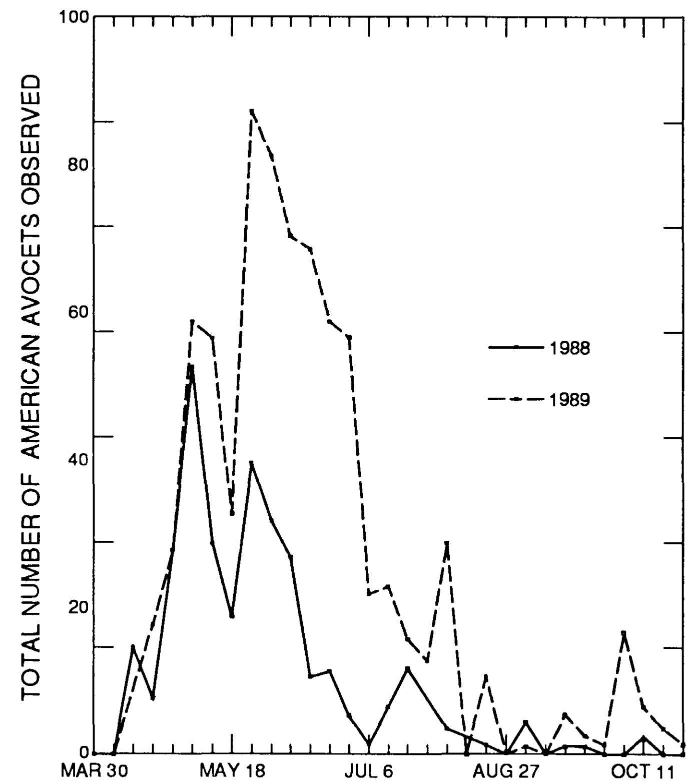


Figure 33.--Total number of American avocets observed in the Kendrick area and at Illco Pond during weekly surveys from March through October, 1988 and 1989.

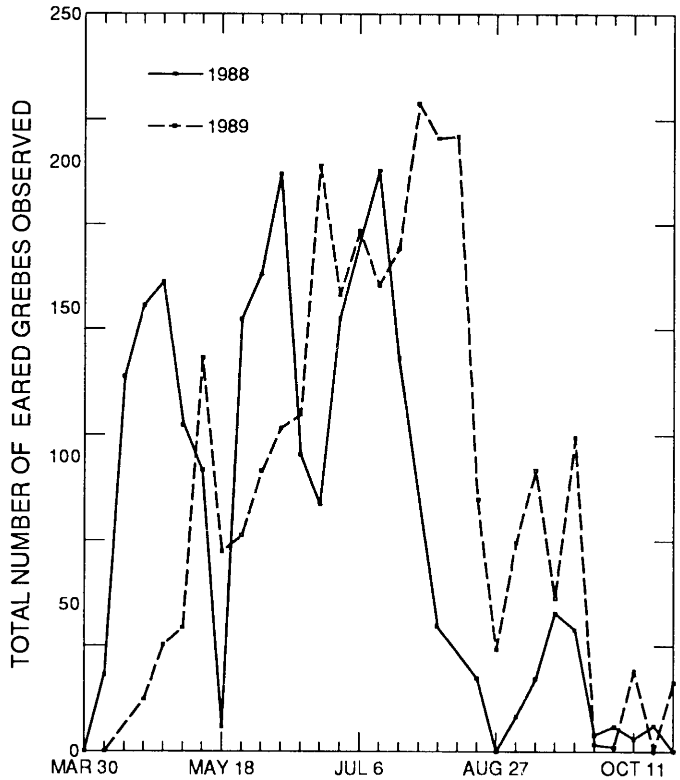


Figure 34.--Total number of eared grebes observed in the Kendrick area and at Illco Pond during weekly surveys from March through October, 1988 and 1989.

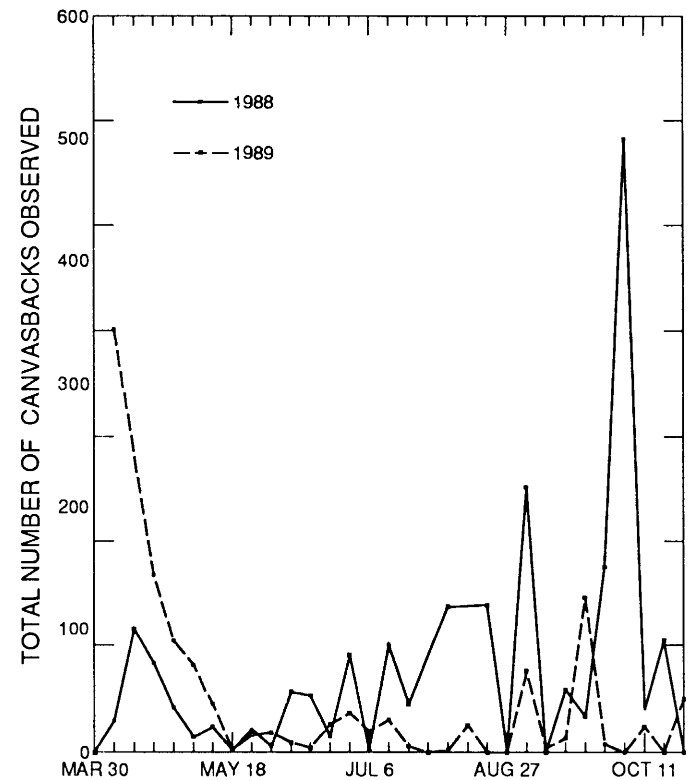


Figure 35.--Total number of canvasbacks observed in the Kendrick area and at Illco Pond during weekly surveys from March through October, 1988 and 1989.

Table 15.--Aquatic bird species observed in the Kendrick Reclamation Project area and at Illco Pond during 1988 and 1989

Common name	Species
Western grebe	*Aechmophorus clarkii*
Eared grebe	*Podiceps nigricollis*
Pied-billed grebe	*Podilymbus podiceps*
White pelican	*Pelecanus erythrorhynchos*
Double-crested cormorant	*Phalacrocorax auritus*
Great blue heron	*Ardea herodias*
Snowy egret	*Egretta thula*
White-faced ibis	*Plegadis chihi*
Northern pintail	*Anas acuta*
American widgeon	*Anas americana*
Northern shoveler	*Anas clypeata*
Green-winged teal	*Anas crecca*
Cinnamon teal	*Anas cyanoptera*
Blue-winged teal	*Anas discors*
Eurasian widgeon	*Anas penelope*
Mallard	*Anas platyrhynchos*
Gadwall	*Anas strepera*
Lesser scaup	*Athya affinis*
Redhead	*Athya americana*
Ring-necked duck	*Athya collaris*
Canvasback	*Athya valisineria*
Canada goose	*Branta canadensis*
Bufflehead	*Bucephala clangula*
Trumpeter swan	*Cygnus buccinator*
Common merganser	*Mergus merganser*
Ruddy duck	*Oxyura jamaicensis*
American coot	*Fulica americana*
Sora rail	*Porzana carolina*
Virginia rail	*Rallus limicola*
Killdeer	*Charadrius vociferus*
Black-necked stilt	*Himantopus mexicanus*
American avocet	*Recurvirostra americana*
Spotted sandpiper	*Actitis macularia*
Willet	*Catoptrophorus semipalmatus*
Common snipe	*Gallinago gallinago*
Dowitcher	*Limnodromus* spp.
Long-billed curlew	*Numenius americanus*
Yellowlegs	*Tringa* spp.
Wilson's phalarope	*Phalaropus tricolor*
California gull	*Larus californicus*
Franklin's gull	*Larus pipixcan*
Tern	*Sterna* spp.

Wetlands in and near the Kendrick area attract an abundant and diverse array of migratory birds. Selenium concentrations in most water samples collected from the wetlands exceeded the 5 µg/L Federal freshwater aquatic life criterion for selenium (U.S. Environmental Protection Agency, 1988). Selenium concentrations in water samples collected from Rasmus Lee Lake during snowmelt ranged from about 25 to 1,000 µg/L in 1988 (fig. 29) and coincided with increased aquatic bird use during the spring migration (fig. 36). Aquatic birds using Rasmus Lee Lake during the spring migration could accumulate enough selenium to cause adverse reproductive effects.

Pondweed

Sago pondweed (Potamogeton vaginatus) is the dominant species of submerged aquatic vegetation observed in ponds in the Kendrick area. Pondweed (Potamgeton spp.) constitutes an important dietary item for dabbling ducks (Bellrose, 1980; Keith and Stanislawski, 1960; Munro, 1939; Quay and Critcher, 1965). Diving ducks such as canvasbacks, redheads (Aytha americana), ring-necked ducks (A. collaris), lesser scaups (A. affinis), and buffleheads (Bucephala clangula) also feed on aquatic vegetation such as pondweed (Bellrose, 1980, Jarvis and Noyes, 1986). Ruddy ducks (Oxyura jamaicensis) are primarily vegetarians; pondweed seeds, tubers, and leaves comprise a fifth of their diet in many areas of North America (Cottam and Knappen, 1939).

Except for arsenic, boron, cadmium, and selenium, all other trace elements in pondweed samples were less than reporting limits or less than concentrations known to cause adverse effects to fish and wildlife. Geometric means and ranges of arsenic, boron, and selenium concentrations are given in table 16.

Geometric mean arsenic concentrations in pondweed samples collected from the study area were less than the 30 µg/g dry weight concentration suspected of causing reduced growth in mallard ducklings (U.S. Fish and Wildlife Service, 1987, p. 13). The largest arsenic concentrations were in two samples from Rasmus Lee Lake (40 and 45 µg/g dry weight).

Boron is known to cause adverse reproductive effects to birds (Birge and Black, 1977; Eisler, 1990; Hoffman and others, 1990; Smith and Anders, 1989). Mallards fed diets supplemented with 300 µg/g dry weight boron produced hatchlings with smaller body weights than those of controls. Mallards fed diets supplemented with a boron concentration of 1,000 µg/g dry weight had reduced hatching success or increased embryo mortality (Smith and Anders, 1989). The geometric mean boron concentrations of pondweed samples collected from all sites approached or exceeded 300 µg/g dry weight (table 16).

All but six pondweed samples had cadmium concentrations less than reporting limits. The six pondweed samples with detectable cadmium were from Goose Lake, Illco Pond, and Oxbow Pond; these samples had concentrations ranging from 0.58 to 1.43 µg/g dry weight (0.1 to 0.19 µg/g wet weight), exceeding the recommended wildlife dietary level of 0.1 µg/g wet weight (Eisler, 1985a).

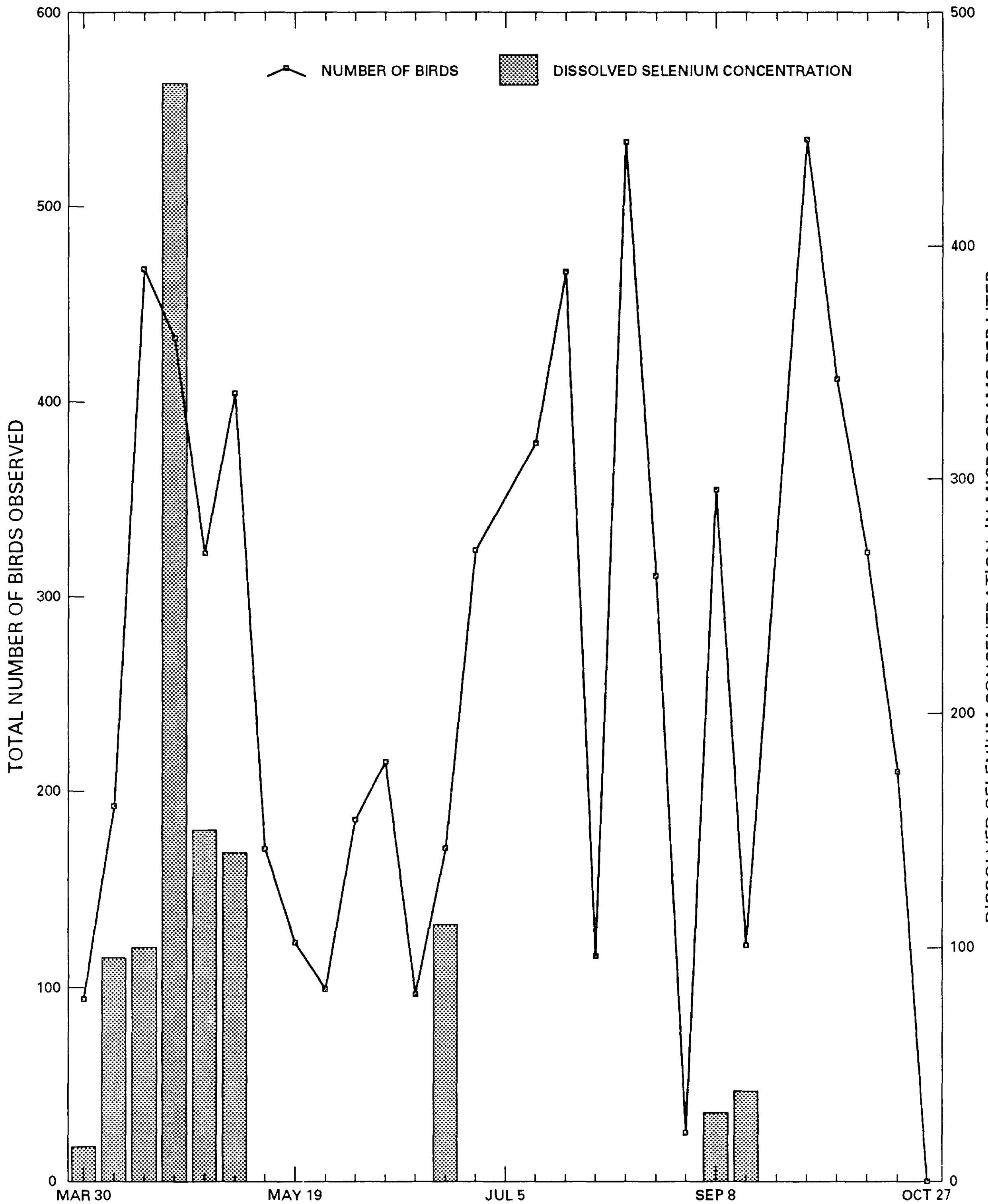


Figure 36.--Aquatic bird use and dissolved-selenium concentrations in water samples collected from Rasmus Lee Lake, March through October, 1988.

Table 16.--Geometric means, ranges, and standard errors of arsenic, boron, and selenium concentrations in pondweed (Potamogeton vaginatus) samples collected during 1988 and 1989

[Concentrations in micrograms per gram dry weight; <, less than reporting limit]

Site	Number of samples	Arsenic			Boron			Selenium		
		Geometric mean	Range	Standard error	Geometric mean	Range	Standard error	Geometric mean	Range	Standard error
Rasmus Lee Lake	11	11.0	4.5-45	4.4	502	350-820	48.6	38.0	13.0-104	8.2
Goose Lake	11	4.0	1.9- 7.0	.5	439	282-818	56.5	14.0	3.3- 28	2.0
Thirtythree Mile Reservoir	7	1.8	1.5- 2.5	.2	299	177-672	79.0	1.0	0.1- 2.8	.4
Illco Pond	7	2.0	0.9- 3.0	.3	471	320-661	48.8	4.4	2.4- 7.6	.9
Oxbow Pond[1]	4	.2	<0.3- 1.6	.4	549	517-584	14.6	2.7	1.8- 3.5	.4
Soda Lake[1]	2	13.0	12.8-13.7	.5	427	426-427	.5	1.1	1.0- 1.2	.07
Dietary level of concern for aquatic birds		Arsenic[2] = 30			Boron[3] = 300			Selenium[4] = 3		

[1] Reference sites.

[2] U.S. Fish and Wildlife Service, 1987, p. 24.

[3] Smith and Anders, 1989, p. 943-950.

[4] Lemly and Smith, 1987.

Selenium concentrations in aquatic vegetation collected from Rasmus Lee and Goose Lakes and Illco Pond were large. In the 1930s, large selenium concentrations in feed grains were associated with embryo mortality and embryo deformities in domestic chickens (Franke and Tully, 1935; Poley and others, 1937). Controlled laboratory studies by Heinz and others (1988) showed that diets containing selenium concentrations of 20, 40, or 80 μg/g dry weight in the form of selenomethionine and sodium selenite caused a decrease in food intake and growth in mallard ducklings. Selenomethionine is reported as the most dominant form of selenium in plants (Heinz and others, 1987). Dietary concentrations of selenium at 80 μg/g dry weight caused 97.5 percent mortality in mallard ducklings (Heinz and others, 1988).

In uncontaminated areas, most plants contain less than 1 μg/g dry weight selenium (Eisler, 1985b; Ohlendorf, 1989). Dietary selenium as selenomethionine in concentrations equal to or greater than 10 μg/g dry weight were associated with reproductive failure in mallards (Heinz and others, 1987). Lemly and Smith (1987) established a selenium concentration of 3 μg/g dry weight in the diet as a level of concern for aquatic birds.

Selenium concentrations in 2 of 11 pondweed samples from Rasmus Lee Lake exceeded 80 μg/g dry weight. Geometric mean selenium concentrations in pondweed stems, leaves, and seeds collected from Rasmus Lee and Goose Lakes and Illco Pond exceeded 3 μg/g dry weight (table 15). Selenium concentrations in pondweed samples from Soda Lake, located east of the Kendrick area were less than 3 μg/g dry weight. A Kruskal-Wallis test did not indicate a significant difference (significance level = 0.05) in selenium concentrations from pondweed samples collected at different times of the irrigation season (May, June, and July).

Aquatic Invertebrates

Aquatic invertebrates inhabited all of the study area ponds where samples of biota were collected for trace element analyses. Aquatic invertebrates, such as damselfly (Odonata) and midge fly (Chironomidae) larvae, water boatmen (Arctocorixa interrupta), and amphipods (Amphipoda) are an important component of aquatic bird diet, particularly among nesting hens and young birds (Bartonek and Hickey, 1969; Jarvis and Noyes, 1986; Krapu, 1974; Reinecke, 1979; Sugden, 1973; Woodin and Swanson, 1989). Aquatic invertebrates are also a major food item for aquatic birds such as avocets and grebes (Bent, 1962; Munro, 1941; Wetmore, 1924; and Williams, 1986). Aquatic invertebrates from uncontaminated areas generally contain concentrations of selenium of less than 4 μg/g dry weight (Eisler, 1985b; Ohlendorf, 1989).

All trace elements in aquatic invertebrates except cadmium and selenium were less than reporting limits or less than concentrations known to cause adverse effects to fish and wildlife. The cadmium concentration in one water boatmen sample from Thirtythree Mile Reservoir was 1.95 μg/g dry weight (0.4 μg/g wet weight). This concentration exceeded the recommended wildlife dietary level of 0.1 μg/g wet weight (Eisler, 1985a).

Geometric mean selenium concentrations in samples of aquatic invertebrates (table 17) collected from wetlands in the Kendrick area and at Illco Pond exceeded the dietary level of concern for aquatic birds (3 μg/g dry weight) and, except for snails, exceeded the dietary level associated with reproductive failure in mallards (10 μg/g dry weight)(Lemly and Smith, 1987).

Table 17. --Selenium concentrations in aquatic invertebrates collected during 1988 and 1989

[Concentrations in micrograms per gram dry weight; --, invertebrate type not observed at site. Selenium dietary level of concern for fish and aquatic birds = 3-5 µg/g dry weight, from Lemly and Smith, 1987]

Site	Number of samples	Geometric mean	Range	Standard error	Number of samples	Geometric mean	Range	Standard error
	Odonates				Chironomids			
Rasmus Lee Lake	2	94.4	87.4-102	7.3	3	158	150 -166	4.6
Goose Lake	1	46.7	--	--	--	--	--	--
Thirtythree Mile Reservoir	--	--	--	--	--	--	--	--
Illco Pond[1]	--	--	--	--	--	--	--	--
Oxbow Pond[1]	1	13.6			4	10.9	6.9- 19.4	2.5
	Water boatmen				Amphipods and copepods			
Rasmus Lee Lake	2	99.1	89.4-110	10.3	--	--	--	--
Goose Lake	1	43.7			9	44.8	36.5- 64.5	3.5
Thirtythree Mile Reservoir	4	14.2	10.3- 17.2	1.5	--	--	--	--
Illco Pond[1]	4	29.7	27.9- 30.7	0.6	--	--	--	--
Oxbow Pond[1]	2	15.9	9.2- 27.4	9.0	--	--	--	--
	Snails							
Rasmus Lee Lake	--	--	--	--				
Goose Lake	--	--	--	--				
Thirtythree Mile Reservoir	--	--	--	--				
Illco Pond[1]	1	--	--	--				
Oxbow Pond[1]	3	3.15	0.9- 25.2	8.0				

[1] Reference site.

Midgefly larvae from Rasmus Lee Lake had the largest selenium concentrations detected in biota samples collected. Water boatmen from Rasmus Lee Lake had geometric mean selenium concentrations of 99.1 μg/g dry weight, substantially larger than other sites. Selenium concentrations in all aquatic invertebrate samples from Rasmus Lee Lake exceeded 80 μg/g dry weight, a concentration shown to cause 98 percent mortality in mallard ducklings (Heinz and others, 1987). Selenium concentrations in water boatmen from all sites ranged from 9.2 to 110 μg/g dry weight. Amphipods and copepods were the dominant aquatic invertebrates found at Goose Lake and contained geometric mean selenium concentrations of 44.8 μg/g dry weight.

Fish

Concentrations of all trace elements (except mercury, lead, and selenium) in samples of fish were at less than reporting limits or less than concentrations known to cause adverse effects. Mercury concentrations less than 0.1 μg/g wet weight are recommended in aquatic organisms for the protection of avian predators that eat fish (Eisler, 1987). Cutthroat trout (Salmo clarki) collected from Goldeneye Reservoir had whole-body mercury concentrations ranging from 0.08 to 0.15 μg/g wet weight (0.26 to 0.52 μg/g dry weight). The geometric mean mercury concentration in whole-body cutthroat trout (0.10 μg/g wet weight, 0.35 dry weight) exceeded the National Contaminant Biomonitoring Program (NCBP) 85th percentile concentration (0.17 μg/g wet weight).

Since 1967, the U.S. Fish and Wildlife Service has participated in the NCBP, formerly the National Pesticide Monitoring Program. Selected organochlorine compounds and toxic trace elements have been analyzed in samples of fish and wildlife collected from a nationwide network of stations.

If comparisons are possible and trace-element and organochlorine-pesticide residues are less than or equal to 85-percent baseline values from the NCBP, then it is safe to say that the concentrations are not large in relation to national-baseline values. By contrast, if the residues are larger than the 85-percent baseline, it is reasonable to state that the concentrations are large in relation to national-baseline values. Although some concentrations might be large in relation to national-baseline levels, this does not mean that the residue levels have resulted or will result in adverse biological effects.

Rainbow trout (Salmo gairdneri) collected from reaches of the North Platte River downstream from the junctions of the Oregon Trail Drain and Casper Creek had geometric mean whole-body mercury concentrations of 0.11 and 0.16 μg/g wet weight (0.07 and 0.7 μg/g dry weight). Rainbow trout from the site downstream from Grey Reef Dam contained mercury concentrations less than the NCBP 85th percentile concentration (0.17 μg/g wet weight) (Schmitt and Brumbaugh, 1990).

Lead concentrations in all samples of fish were less than reporting limits, with the exception of one cutthroat trout collected from Goldeneye Reservoir and two rainbow trout collected from the North Platte River downstream from the junction of Poison Spider Creek and the river. Whole-body lead concentrations in these three fish ranged from 1.55 to 2.32 μg/g wet weight (6.89 to 7.97 μg/g dry weight), exceeding the NCBP 85th percentile concentration (0.22 μg/g wet weight) (Schmitt and Brumbaugh, 1990). Lead concentrations in muscle tissue from these three trout ranged from 1.5 to 2.3 μg/g wet weight (6.9 to 7.97 μg/g dry weight), exceeding levels known to cause severe spinal deformities in brook trout (Salvelinus fontinalis) (Holcombe and others, 1976).

Large selenium concentrations in water are known to cause adverse effects to carp. Sato and others (1980) determined that carp began to die after 7 days of exposure to selenium concentrations of 10 mg/L and after 3 days of exposure to selenium concentrations of 50 mg/L in water. Effects were noted in carp with whole-body selenium concentrations greater than 5 μg/g wet weight, and death occurred at concentrations greater than 10 μg/g wet weight. Lemly and Smith (1987) determined that whole-body selenium concentrations exceeding 12 μg/g dry weight could impair reproduction in fish.

The whole-body geometric mean selenium concentration in carp collected from Thirtythree Mile Reservoir and Illco Pond exceeded 12 μg/g dry weight, the concentration that could impair reproduction in fish (table 18). Geometric mean selenium concentrations in carp from Thirtythree Mile Reservoir and Illco Pond exceeded the NCBP 85th percentile concentration of 0.73 μg/g wet weight (3 μg/g dry weight) for carp. Carp collected from Illco Pond had whole-body selenium concentrations greater than 5 μg/g wet weight (19.7 μg/g dry weight). Carp collected from Goldeneye Reservoir, a reference site, had whole-body selenium concentrations less than 12 μg/g dry weight and did not exceed the 85th percentile concentration of 0.73 μg/g wet weight (3 μg/g dry weight) for carp collected in the NCBP (Schmitt and Brumbaugh, 1990). Selenium concentrations in carp from Thirtythree Mile Reservoir and Illco Pond were significantly larger (Tukey's multiple range test, significance level = 0.05) than in carp from Goldeneye Reservoir (table 18).

Black bullhead collected from Thirtythree Mile Reservoir had whole-body selenium concentrations ranging from 12.0 to 16.0 μg/g dry weight (2.6 to 2.8 μg/g wet weight)(table 18). These concentrations are equal to or greater than the 12 μg/g dry weight concentration suspected of causing adverse reproductive effects in fish (Lemly and Smith, 1987).

Selenium concentrations in one green sunfish (17.0 μg/g dry weight) collected from Thirtythree Mile Reservoir and two brassy minnows from Illco Pond exceeded the 12 μg/g dry weight level of concern (Lemly and Smith, 1987). Whole-body selenium concentrations in all but one of the white suckers (Catostomus commersoni) collected from Goldeneye Reservoir were less than the 85th percentile concentration (0.73 μg/g wet weight or 3 μg/g dry weight) reported in the NCBP (Schmitt and Brumbaugh, 1990).

Lemly and Smith (1987) reported that selenium concentrations larger than 16 μg/g dry weight in liver tissue and larger than 8 μg/g dry weight in muscle tissue caused reproductive failure in trout. Hilton and others (1980) detected selenium concentrations of 100 μg/g dry weight in livers of trout that exhibited reduced growth, poor feeding efficiency, and mortality after exposure to 10 μg/g dry weight of selenium in the diet. Livers from rainbow trout collected from the North Platte River immediately downstream from the junctions of Poison Spider Creek, Oregon Trail Drain, and Casper Creek contained selenium concentrations exceeding 100 μg/g dry weight (table 18).

Table 18.--Selenium concentrations in fish (whole body) collected from Thirtythree Mile Reservoir, Illco Pond, and Goldeneye Reservoir, 1988

[Concentrations in micrograms per gram (μg/g) dry weight; selenium concentrations equal to or greater than 12 μg/g dry weight are suspected of causing adverse reproductive effects in fish (Lemly and Smith, 1987). --, species not collected at that site]

Site	Number of samples	Geometric mean	Range	Standard error	Number of samples	Geometric mean	Range	Standard error
	Carp				Black bullhead			
Thirtythree Mile Reservoir	6	25.3	16.0- 37.0	24.5	3	13.6	12.0 -16.0	1.2
Illco Pond	3	33.6	21.0- 41.0	39.0	--	--	--	--
Goldeneye Reservoir[1]	5	1.90	1.6- 2.4	.1	--	--	--	--
	Brassy minnow				White sucker			
Thirtythree Mile Reservoir	--	--	--	--	--	--	--	--
Illco Pond	2	24.5	23.0 -26.0	1.5	--	--	--	--
Goldeneye Reservoir[1]	--	--	--	--	5	2.17	1.71- 2.64	.15
	Green sunfish							
Thirtythree Mile Reservoir	1	17.0	--	--				
Illco Pond	--	--	--	--				
Goldeneye Reservoir[1]	--	--	--	--				

[1] Reference site.

Selenium concentration in a composite liver sample from rainbow trout collected from the North Platte River downstream from Grey Reef Reservoir was substantially smaller than selenium concentrations in trout livers collected from the North Platte River reaches receiving irrigation drainwater (table 19).

Table 19.--Selenium concentrations in livers from rainbow trout collected in the North Platte River, 1988

[Concentrations in micrograms per gram dry weight]

Sampling site	Selenium concentration[1]
North Platte River downstream from Grey Reef Reservoir[2]	49
North Platte River downstream from Poison Spider Creek	121
North Platte River downstream from Oregon Trail Drain	250
North Platte River downstream from Casper Creek	138

[1]Five liver samples from each site composited into one sample for analysis.

[2]Reference site.

Lemly and Smith (1987) reported that selenium concentrations in trout muscle tissue larger than 8 $\mu g/g$ dry weight caused reproductive failure. Selenium concentrations in samples of muscle tissue from five rainbow trout collected in the North Platte River immediately downstream from Grey Reef Dam (reference site) ranged from 2.39 to 3.63 $\mu g/g$ dry weight (0.54 to 0.89 $\mu g/g$ wet weight). Cutthroat trout from Goldeneye Reservoir (reference site) and rainbow trout from Dan Speas Fish Hatchery (reference site) had selenium concentrations in samples of muscle tissue ranging from 0.88 to 2.61 $\mu g/g$ dry weight (0.22 to 0.65 $\mu g/g$ wet weight). Selenium concentrations in samples of muscle tissue from rainbow trout collected at sites along the North Platte River downstream of tributary inflows of irrigation drainwater ranged from 7.92 to 14.9 $\mu g/g$ dry weight (2.22 to 3.76 $\mu g/g$ wet weight) (fig. 37). Water from the Kendrick area enters the North Platte River and contributes to

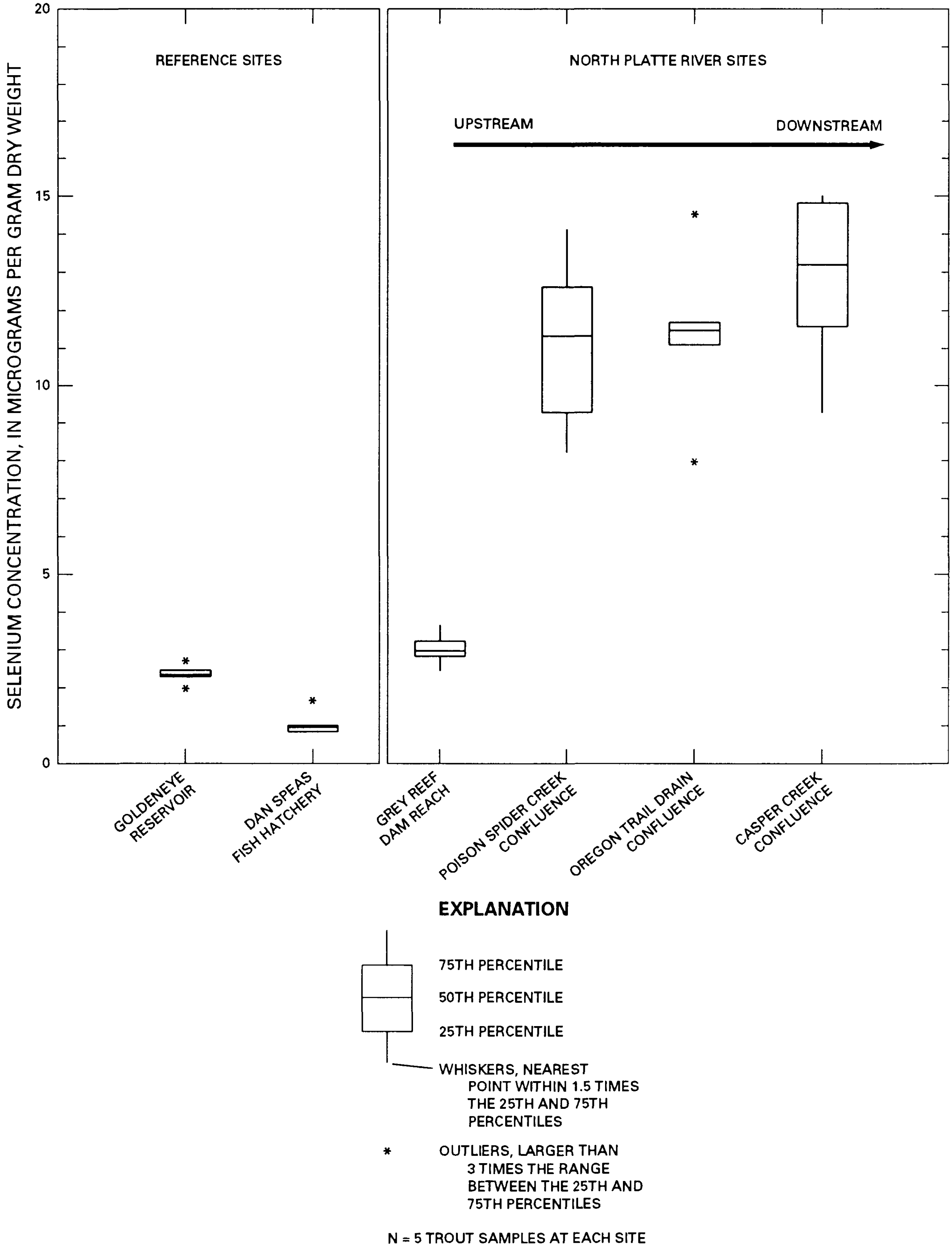


Figure 37.--Selenium concentrations in muscle-tissue samples of rainbow trout collected from the North Platte River and reference sites, 1988.

selenium accumulation in the trout fishery. Although fish accumulate selenium by consuming contaminated food, such as aquatic invertebrates, they also take up this element directly from the water (Hodson and others, 1980; Hodson and Hilton, 1983; Lemly, 1982). The effect of selenium concentrations in the North Platte River is cumulative; selenium concentrations in water samples (fig. 12) and samples of rainbow trout muscle tissue increase downstream (fig. 37).

Selenium concentrations in trout muscle tissue equate to whole-body residues of about 13.2 to 24.8 μg/g dry weight (3.7 to 6.2 μg/g wet weight) using the following conversion factor (Lemly and Smith, 1987):

$$\text{Whole-body concentration} = \frac{\text{muscle-tissue concentration}}{0.6}$$

These whole-body selenium concentrations are greater than the 2 μg/g wet weight reported by Baumann and May (1984) that could cause reproductive problems in fish. These concentrations are also within the range (10-30 μg/g dry weight) that caused mortality in rainbow trout (Gissel-Nielson and Gissel-Nielson, 1978) and that caused reduced survival and growth in another salmonid, chinook salmon (Oncorhynchus tschawytscha) (Hamilton and others, 1990). Selenium concentrations in trout muscle tissue from the reference sites equate to whole-body residues of about 1.5 to 6.05 μg/g dry weight (0.36 to 1.5 μg/g wet weight). As a comparison, the national geometric mean of whole-body selenium concentrations in fish collected for the NCBP in 1984 was 0.42 μg/g wet weight (Schmitt and Brumbaugh, 1990).

The National Academy of Sciences (NAS) recommended a daily intake of selenium for humans not to exceed 200 μg/d and an upper safe limit of 775 μg/d per adult male for chronic oral consumption (Combs and Combs, 1986). Daily consumption of 2 oz wet weight of fish from the reach downstream from the Casper Creek junction and 4 oz of fish from the reach downstream from the Poison Spider Creek junction would provide about 200 μg/d of selenium; 7 oz wet weight of fish from the reach downstream of the Casper Creek junction would provide about 775 μg/d of selenium. Fillets from rainbow trout collected from the North Platte River averaged 4 oz wet weight and ranged from 1 to 10 oz. The trout collected ranged from 7 to 17 in. in length and averaged 12 in. in length.

Aquatic Birds

All trace elements in aquatic bird livers and eggs other than lead and selenium were less than reporting limits or less than concentrations known to cause adverse effects to aquatic birds. The liver of a lesser scaup carcass found dead in the study area contained a lead concentration of 19.6 μg/g dry weight; a concentration of 10 μg/g dry weight is indicative of lead poisoning (Eisler, 1988). Concentrations of lead were detected in 3 out of 151 eared grebe eggs and ranged from 5.82 to 10.5 μg/g dry weight. Twelve of 102 American avocet eggs contained lead concentrations ranging from 5.05 to 11.4 μg/g dry weight. Seven of 115 Canada goose eggs contained lead concentrations ranging from 5.03 to 15 μg/g dry weight.

Geometric mean selenium concentrations in livers from all birds collected from the Kendrick area exceeded 30 μg/g dry weight (table 20), except for three juvenile Canada goose carcasses recovered from Rasmus Lee Lake. Selenium concentrations greater than 30 μg/g dry weight in bird livers are associated with biological risk, and concentrations as small as 10 μg/g are considered greater than background concentrations (U.S. Fish and Wildlife Service, 1990). Selenium concentrations greater than 6.9 μg/g wet weight were detected in livers from mallard ducklings that died after exposure to a diet containing a selenium concentration of 40 and 80 μg/g dry weight (Heinz and others, 1988). Assuming a moisture content of 75 percent, the 6.9 μg/g wet weight concentration of selenium in mallard duckling livers is equivalent to 27.6 μg/g dry weight.

Geometric mean selenium concentrations in bird eggs exceeding 3 μg/g dry weight are characteristic of contamination greater than background concentrations, and geometric mean selenium concentrations exceeding 8 μg/g dry weight are associated with impaired egg hatchability (Skorupa and Ohlendorf, 1991). Geometric mean selenium concentrations were greater than background concentrations (3 μg/g dry weight) in eggs from Canada geese, American avocets, eared grebes, Wilson's phalaropes, and dabbler ducks (Anas spp.) collected in the Kendrick area (table 21). American avocet and eared grebe eggs had geometric mean selenium concentrations associated with impaired egg hatchability (greater than 8 μg/g dry weight)(Skorupa and Ohlendorf, 1991).

Selenium concentrations in samples of breast muscle tissue from juvenile Canada geese collected during 1988 and 1989 from Rasmus Lee and Goose Lakes prior to fledging ranged from 18.8 to 35.2 μg/g dry weight (table 22). Selenium in the samples of breast muscle tissue of adult ducks collected in September 1988 ranged from 1.98 μg/g dry weight in a ruddy duck to 18.5 μg/g dry weight in a mallard (table 22). Geometric mean selenium concentrations in samples of breast muscle tissues from juvenile Canada geese, an adult green-winged teal, and mallards exceeded the 2 μg/g dry weight concentration detected in samples of breast muscle tissue from mallards experiencing impaired reproduction in a controlled dietary selenium study (Heinz and others, 1987). Selenium concentrations in samples of the breast muscle tissue from a ruddy duck approached the 2 μg/g dry weight concentration. The source of selenium in the Canada geese can be linked to the Kendrick area because the goslings were incapable of flight and were observed feeding in and around Rasmus Lee and Goose Lakes. The selenium concentrations in samples of the adult duck breast muscle tissues cannot be linked directly to the Kendrick area because these birds were capable of flight and could have accumulated selenium from other sources outside the Kendrick area.

These data can be used as a guide in assessing the selenium exposure to human consumers of waterfowl from this area. Consumption of 2 to 8 oz of mallard breast muscle tissue or 1.5 to 5.5 oz of Canada goose breast muscle tissue from the Kendrick area could provide from about 200 to 750 μg of selenium to human consumers; this range of selenium concentration is recognized as possible daily maximum concentration of selenium for adult human males (Combs and Combs, 1986).

Table 20.--Selenium concentrations in samples of aquatic bird livers collected during 1988 and 1989

[Concentrations in micrograms per gram (μg/g) dry weight; --, range not available]

Species	Site	Number of samples	Geometric mean	Range	Percentage of samples exceeding 30 μg/g[1]
		Live birds collected by investigators			
Canada goose[2]	Rasmus Lee Lake	10	35.6	21.4-62.1	70
American avocet[2]	Goose Lake	4	75.9	57.6-94.2	100
	Soda Lake	2	36.5	31.9-41.0	100
Eared grebe[2]	Goose Lake	4	74.2	37.9-112	100
Eared grebe[3]	Goose Lake	5	77.7	51.4-134	100
Eared grebe[2]	Soda Lake	2	33.3	24.5-42.0	50
Eared grebe[3]	Soda Lake	2	24.4	23.4-25.4	0
Dabbler ducks[2]	Kendrick area	12	35.1	7.6-39.7	50
Blue-winged teal[2]	Soda Lake	1	[4]70.5	--	100
		Bird carcasses found dead			
Canada goose[3]	Rasmus Lee Lake	3	3.75	2.6-4.9	0
Eared grebe[2]	Goose Lake	2	97.5	95.0-100	100
Eared grebe[3]	Goose Lake	1	[4]81.3	--	100
American avocet[2]	Goose Lake	1	[4]54.0	--	100
American coot[2]	Kendrick area	4	70.9	39.5-125	100
Lesser scaup[2]	Kendrick area	1	[4]79.7	--	100
Wilson's phalarope[2]	Goose Lake	1	[4]34.5	--	100
Green-winged teal[2]	Goose Lake	1	[4]30.7	--	100
Ruddy duck[2]	Goose Lake	1	[4]93.0	--	100

[1]Concentration associated with biological risk (U.S. Fish and Wildlife Service, 1990).

[2]Samples from live adult birds.

[3]Samples from juvenile birds.

[4]Concentration in the one sample.

Table 21.--Selenium concentrations in aquatic bird eggs collected during 1988 and 1989

[Concentrations in micrograms per gram dry weight]

	Number of samples	Geometric mean[1]	Range
Canada goose	115	7.5	2.4-29.8
American avocet	102	82.7	24.2-135
Eared grebe	151	75.1	39.4-121
Dabbler ducks	6	13.1	7.7-52.5
Wilson's phalarope	6	11.7	5.0-19.9

[1]Threshold geometric mean concentrations of selenium in eggs, in micrograms per gram dry weight (Skorupa and Ohlendorf, 1991):

Less than 3 - Background concentrations from uncontaminated aquatic bird populations.
8 - Associated with impaired egg hatchability in American avocets and eared grebes.
Greater than 13 - Associated with teratogenic populations of aquatic birds in western and northern plains states.

Table 22.--Selenium concentrations in samples of breast-muscle tissue of adult ducks and juvenile Canada geese collected during 1988 and 1989

[Concentrations in micrograms per gram; --, no data]

Species	Number of samples	Dry weight: Geometric mean	Dry weight: Range	Wet weight: Geometric mean	Wet weight: Range
Canada goose	9	25.09	18.8-35.2	4.78	2.95-7.32
Green-winged teal	2	2.17	2.0-2.4	.58	0.53-0.64
Mallard[1]	4	12.55	6.0-18.5	3.41	1.63-5.07
Ruddy duck	1	1.98	--	.50	--
Northern shoveler	1	10.60	--	2.77	--

[1]Selenium concentrations greater than 2 μg/g dry weight were found in breast muscle tissues of mallards experiencing impaired reproduction in a controlled dietary selenium study (Heinz and others, 1987).

Necropsies

Aquatic bird carcasses found in the Kendrick area were submitted for necropsy, and results are shown in table 23. Selenium toxicosis was diagnosed as a possible cause of death in a juvenile eared grebe carcass with a deformed bill found at Goose Lake. Emaciation, although a diagnostic feature of selenium toxicosis, could have been caused by intestinal parasites in three of the carcasses. Selenium concentrations in livers from these carcasses were large and might have contributed to the death of these birds.

Bird Reproduction

Avian embryos particularly are sensitive to excessive concentrations of selenium (Arnold and others, 1972; El-Begearmi and others, 1977; National Academy of Science, 1976; Ort and Latshaw, 1978; Poley and Moxon, 1938; Thapar and others, 1969). Selenium causes embryo mortalities and developmental abnormalities in aquatic birds (Hoffman and others, 1988; Hoffman and Heinz, 1988; Ohlendorf and others, 1986a, 1986b, 1989). Ohlendorf and others (1986b) determined that selenium concentrations in aquatic bird eggs reflected the dietary concentration of selenium, and the probability of embryo death or deformity increased substantially as selenium concentration in the egg increased. Skorupa and Ohlendorf (1991) also showed a clear dose-response relation between the average selenium concentrations in eggs and the occurrence of teratogenesis (embryo deformities, particularly multiple malformations) in aquatic bird populations from various sites in California, Montana, Nevada, Oregon, Utah, and at the Kendrick area in Wyoming.

Adverse reproductive effects, such as embryo mortality and teratogenesis, associated with bioaccumulation of selenium were observed for Canada geese, American avocets, and eared grebes at the Kendrick area. Reduced hatchability and nest success also have been associated with selenium toxicity in aquatic bird eggs (Ohlendorf and others, 1989; Skorupa and Ohlendorf, 1991). Egg hatchability is a more sensitive indicator of selenium contamination than teratogenesis. Skorupa and Ohlendorf (1991) identified lower mean egg selenium concentrations in aquatic bird eggs with impaired hatchability than in eggs with teratogenesis.

The primary visible effect of selenium compounds transmitted to the embryo is cellular necrosis in the brain, spinal cord, optic cups, lens vesicles, limb buds, and tail region (Gruenwald, 1958). The necrosis often causes malformations such as: hydrocephaly, an accumulation of fluid around the brain; microphthalmia and anopthalmia, defects of the eyes; ectrodactyly, defects of the feet; ectromelia, micromelia, and amelia, defects of limbs; and deformities of the bill (Birge and Roberts, 1976; Franke and Tully, 1935; Heinz and others, 1987; Hoffman and Heinz, 1988; Ohlendorf and others, 1986a).

Embryo deformities associated with large selenium concentrations at the Kendrick area were observed in Canada geese, American avocets, and eared grebes. The incidence of major external malformations in uncontaminated wild bird populations is normally less than 1 percent (Austin, 1969; Gilbertson and others, 1976; Hill and Hoffman, 1984; Pomeroy, 1962; Smith and Diem, 1971; Threlfall, 1968). The frequency of gross malformations in embryos of Canada geese, American avocets, and eared grebes at the Kendrick area exceeded 1 percent in one of two nesting seasons studied (table 24).

Table 23.--Necropsy results and selenium concentrations in samples of livers from aquatic bird carcasses collected during 1989

[Concentrations in micrograms per gram dry weight; --, no data]

Species	Remarks/diagnosis	Selenium concentration
Canada goose (juvenile)	Emaciated, multiple sections of intestine contained numerous nematode parasites. Diagnosis: intestinal nematodiasis.	21.4
American avocet (adult)	Advanced autolysis. Diagnosis: cause of death undetermined.	54.0
Eared grebe (juvenile)	Moderate deviation of the bill to the right of the bird. All internal organs normal. Diagnosis: deformity of bill is compatible with selenium toxicity.	81.3
Eared grebe (juvenile)	Grossly normal. Diagnosis: cause of death undetermined.	--
Canada goose (juvenile)	Emaciated, multiple sections of intestine contained numerous	21.4
Western grebe (adult)	Internal organs normal. No external injuries noted. Diagnosis: cause of death undetermined.	--
Ruddy duck (adult)	Emaciated, multiple sections of intestine contained numerous nematode parasites. Diagnosis: intestinal nematodiasis.	93.0
Mallard (juvenile)	Emaciated, multiple sections of intestine contained numerous nematode parasites. Diagnosis: intestinal nematodiasis.	--

Table 24.--Frequency of embryonic malformations and mean selenium concentrations in aquatic-bird eggs from Rasmus Lee and Goose Lakes during 1988 and 1989

[N, number; concentrations in micrograms per gram dry weight; --, gross malformations not observed]

Species	Year	Percent of malformed embryos (N)	Sample size[1]	Observed number of gross malformations: Eyes	Legs/feet	Bills	Hydrocephaly	Wings	Selenium concentrations in eggs: Geometric mean: Malformed embryos	Nesting population[2]	Equals or exceeds teratogenetic threshold[3]
Canada goose	1988	15 (2)	13	2	--	--	--	--	3.2	5.5	No
	1989	0 (0)	35	--	--	--	--	--	--	9.8	No
Total		4 (2)	48	2	--	--	--	--	3.2	7.7	No
American avocet	1988	0 (0)	2	--	--	--	--	--	--	68.4	Yes
	1989	24 (9)	37	2	8	5	3	2	109	85.8	Yes
Total		23 (9)	39	2	8	5	3	2	109	82.8	Yes
Eared grebe	1988	6 (1)	16	1	--	--	--	--	64.8	74.0	Yes
	1989	12 (4)	34	3	--	--	1	--	88.3	78.8	Yes
Total		10 (5)	50	4	--	--	1	--	82.9	75.2	Yes

[1]Number of random and nonrandom late-stage (equal to or greater than one-half incubation term) embryos examined.

[2]Includes all random and nonrandom eggs that were collected at nest sites and analyzed for selenium.

[3]The threshold range for mean egg selenium associated with teratogenesis (embryo malformations) in aquatic bird populations is 13-24 micrograms per gram dry weight (Skorupa and Ohlendorf, 1991).

Some embryos were too decomposed for complete examination, particularly for eye and brain abnormalities; hence, only gross external malformations were noted. Microphthalmia was the only deformity observed in goose embryos from Rasmus Lee Lake. However, one goose embryo had hemorrhaged over its entire body surface. Multiple gross malformations were not observed in goose or grebe embryos; however, 44 percent of deformed avocet embryos exhibited multiple defects. Hydrocephaly, microphthalmia, anophthalmia, micromelia, amelia, ectromelia, ectrodactyly, and bill deformities were observed in avocet embryos from Rasmus Lee Lake; crossed bills and malformed legs and feet were most common (table 24). In contrast, a crossed bill was only observed in one dead grebe chick collected from Goose Lake. The bill deformation in the grebe chick was not recognized initially, but was discovered upon necropsy. Bill deformities might have gone undetected in grebe embryos because they were not as apparent as those observed in avocet embryos. Anophthalmia, microphthalmia, and hydrocephaly were the primary malformations observed in grebe embryos.

A threshold concentration range of 13 to 24 μg/g dry weight mean egg selenium is associated with teratogenic populations of aquatic birds (Skorupa and Ohlendorf, 1991). Geometric mean selenium concentrations of American avocet and eared grebe eggs collected in the Kendrick area exceeded the upper limit of this threshold for teratogenic populations (table 24). Therefore, the gross malformations observed in avocet and grebe embryos presumably resulted from selenium toxicosis. In contrast, geometric mean selenium concentrations in eggs from Canada geese were less than the range of values associated with teratogenesis. Other factors apart from or aggravated by selenium contamination might explain the goose embryo abnormalities observed in 1988.

The frequency of embryo malformations in aquatic birds at Kesterson was 33.9 percent in nests and 16.1 percent in eggs (Hoffman and others, 1988, p. 520; Ohlendorf and others, 1986a, p. 52). The frequency of malformed embryos in nests and eggs of aquatic birds in 1988 and 1989 at the Kendrick area (table 25) was much lower than that found at Kesterson, yet exceeded the frequency of malformations found at the uncontaminated Volta Wildlife Area (Volta) in California. At Volta, no abnormal embryos were observed in aquatic birds (Hoffman and others, 1988, p. 520). Embryo malformations in all species were more common in 1989 than in 1988 at the Kendrick area.

Aquatic bird embryo mortality at Volta occurred in 3.2 percent of the nests and 0.7 percent of the eggs. The frequencies of embryo mortality in aquatic birds at Kesterson were 40.6 percent in nests and 14.6 in eggs (Hoffman and others, 1988, p. 520; Ohlendorf and others, 1986a, p. 52). The frequencies of embryo mortalities in nests and eggs at the Kendrick area exceeded those at Volta (table 25). In addition, the frequency of embryo mortality in eggs at the Kendrick area approached or exceeded that at Kesterson. The frequency of embryo mortality in nests at the Kendrick area in 1989 approached that at Kesterson; however, in 1988 it was lower (table 25). Estimates of embryo mortalities in avocets and geese at the Kendrick area may be conservative. Some eggs recorded as infertile could have contained undeveloped, dead embryos because most eggs examined were decomposed or desiccated eggs.

Table 25.--Frequency of grossly malformed and dead embryos from aquatic-bird nests and eggs and selenium concentrations in eggs at Rasmus Lee and Goose Lakes during 1988 and 1989

[Concentrations in micrograms per gram dry weight; N, number of samples]

		Frequency of occurrence						Selenium concentrations in eggs[1]
		Malformed embryos			Dead embryos			Geometric mean ± standard error
Species	Year	[2]N	Number	Percent	[3]N	Number	Percent	
Canada goose	1988							5.51 ± 0.26
Nests		14	1	7	14	8	57	
Eggs		72	1	1	72	21	29	
American avocet								68.4 ± 5.78
Nests		8	0	0	8	3	38	
Eggs		33	0	0	33	4	12	
Eared grebe								74.0 ± 1.32
Nests		97	1	1	99	16	15	
Eggs		276	1	0	281	20	8	
Total								36.2 ± 2.47
Nests		119	2	2	121	27	22	
Eggs		381	2	1	386	45	12	
Canada goose	1989							9.8 ± .82
Nests		21	0	0	22	15	68	
Eggs		108	0	0	113	40	35	
American avocet								85.8 ± 2.10
Nests		44	6	14	47	23	49	
Eggs		161	9	6	174	52	30	
Eared grebe								78.8 ± 2.01
Nests		55	2	4	57	11	19	
Eggs		128	2	2	132	15	11	
Total								38.7 ± 2.76
Nests		120	8	7	126	49	39	
Eggs		397	11	3	419	107	26	

[1] Includes random and nonrandom eggs collected at nest sites and analyzed for selenium.

[2] Includes nests or eggs monitored to hatching or from which a late-stage (≥ one-half incubation term) embryo was examined.

[3] Includes nests or eggs monitored to hatching or from which an embryo was examined.

Selenium concentrations in aquatic bird eggs at the Kendrick area were significantly larger (Kruskal-Wallis significance level = 0.05) in 1989 than in 1988 and could explain the larger incidence of embryo mortality and malformations in 1989 (table 25). At Rasmus Lee and Goose Lakes, water levels appeared lower in 1989 than in 1988. Selenium concentrations in water at the Kendrick area wetlands likely would increase in drier years resulting in increased accumulation throughout the food chain. Water and sediment samples were not collected during 1989 from Kendrick area wetlands, and sample sizes of aquatic vegetation and invertebrates were insufficient for reliable comparisons. However, selenium concentrations in eggs presumably would vary with selenium concentrations throughout the wetland ecosystem.

Although embryos died at all stages of incubation, embryo mortalities occurred most frequently in the third and fourth week of incubation in Canada geese, in the first and third week of incubation in American avocets, and in the third or last week of incubation in eared grebes (fig. 38). Embryo death in the first week of incubation likely is underestimated because some undeveloped embryos probably were not detected.

Some embryos exhibited reduced growth when age, based on nest visitation dates, is compared to apparent developmental stage. For example, avocet eggs that were pipped should be about 20 days old, but the embryos appeared to be closer to 15 days old on the basis of their developmental stage. Stunted embryonic growth was observed in mallards fed diets containing a selenomethionine concentration of 10 μg/g and a sodium selenite concentration of 25 μg/g (Hoffman and Heinz, 1988, p. 477). During 1988 and 1989, the geometric mean selenium concentrations in pondweed and aquatic invertebrates eaten by Canada geese, American avocets, and eared grebes at Rasmus Lee and Goose Lakes ranged from 14 μg/g dry weight for pondweed (table 16) to 158 μg/g dry weight for chironomids (table 17). Thus, it is likely that the stunted embryonic growth observed in aquatic birds at the Kendrick area resulted from selenium contamination.

Embryo mortality was the main cause of egg loss in aquatic birds at Rasmus Lee and Goose Lakes except for eared grebes in 1988 in which a larger percentage of eggs disappeared (table 26). All avocet and grebe eggs and 27 percent of goose eggs exceeded the selenium concentration of 10 μg/g dry weight in an individual egg associated with impaired embryo viability among black-necked stilts at Kesterson (Skorupa and Ohlendorf, 1991).

Hatchability of fertile eggs is considered the most sensitive measure of selenium toxicity in birds (Heinz and others, 1987; Ort and Latshaw, 1978). In experimental studies with chickens (Ort and Latshaw, 1978), Japanese quail (Coturnix japonica) (El-Begearmi and others, 1977) and mallards (Heinz and others, 1987, 1989; Hoffman and Heinz, 1988), dietary concentrations of selenium greater than 7 μg/g dry weight resulted in smaller egg hatchability. Geometric mean selenium concentrations in samples of aquatic vegetation and aquatic invertebrates at Rasmus Lee and Goose Lakes typically consumed by aquatic birds exceeded this dietary concentration (tables 16 and 17).

Egg hatchability in uncontaminated populations of wild aquatic birds normally exceeds 90 percent (Koenig, 1982). Skorupa and Ohlendorf (1991) estimate geometric mean concentration of selenium in eggs of 8 μg/g dry weight as the lower boundary for impaired egg hatchability based on studies of black-necked stilts and American avocets in the Tulare Basin, California. Geometric mean concentration of selenium in eggs from aquatic birds at the Kendrick area

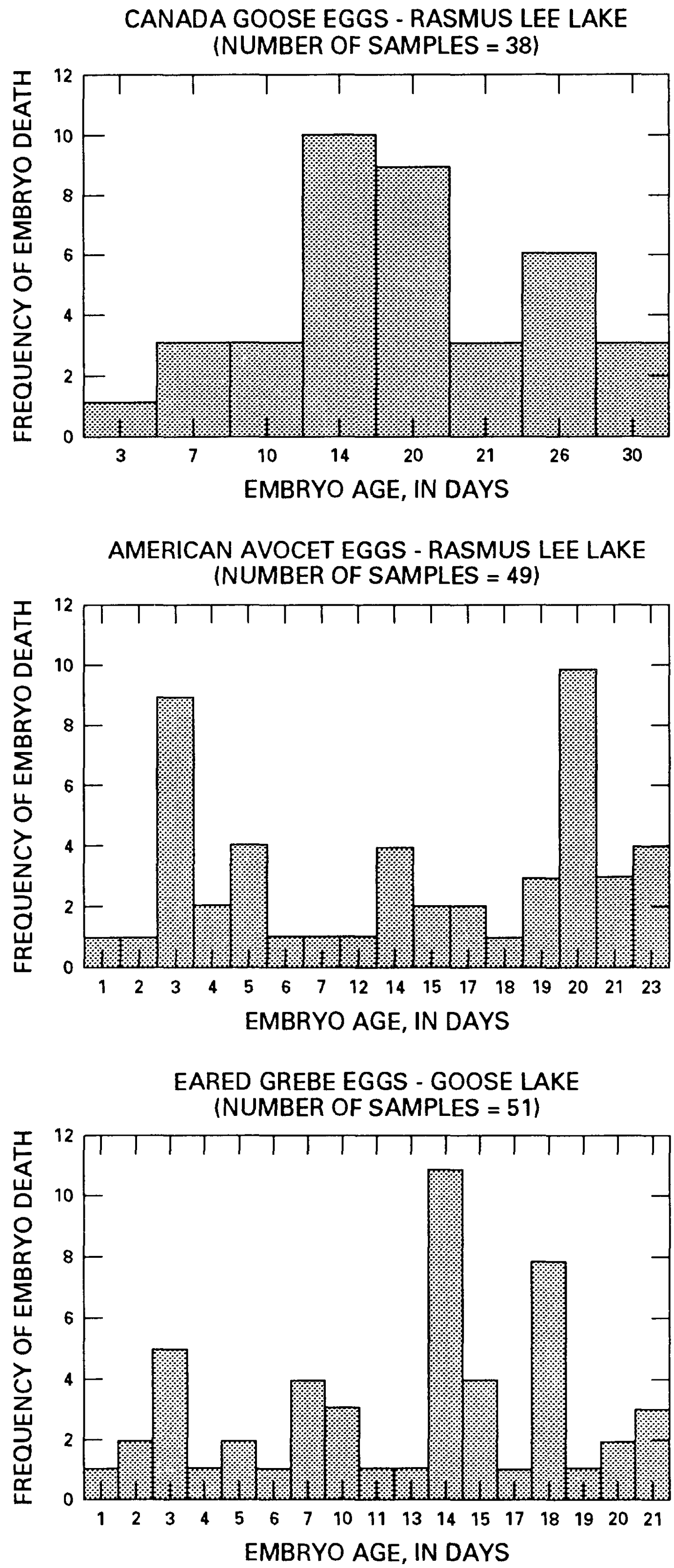


Figure 38.--Estimated age of embryo death for Canada geese, American avocets, and eared grebes from Rasmus Lee and Goose Lakes, 1989.

Table 26.--Estimated losses of aquatic bird eggs monitored at Rasmus Lee and Goose Lakes during 1988 and 1989

[Concentrations in micrograms per gram; N, number; RL, Rasmus Lee Lake; GL, Goose Lake]

				Percent and number of egg losses													
				Embryo mortality				Undeveloped or infertile[3]		Unknown				Chick mortality		Total losses		Selenium concentrations in eggs[6]
				Toxicosis[2]		Abandoned				Missing prior to hatch[4]		Nonviable[5]						Geometric mean ± standard error
Species	Year	Site	Sample[1] size	Percent	(N)	Percent	(N)	Percent	(N)	Percent	(N)	Percent	(N)	Percent	(N)	Percent	(N)	
Canada goose	1988	RL	72	25.0	(18)	4.2	(3)	16.7	(12)	2.8	(2)	0	(0)	1.4	(1)	50.0	(36)	5.5 ± 0.3
Canada goose	1989	RL	125	32.0	(40)	0	(0)	18.4	(23)	0	(0)	0	(0)	0	(0)	50.4	(63)	9.8 ± .8
American avocet	1988	RL GL	34	11.8	(4)	0	(0)	11.8	(4)	0	(0)	8.8	(3)	2.9	(1)	35.3	(12)	68.4 ± 5.8
American avocet	1989	RL GL	197	26.4	(52)	0	(0)	15.2	(30)	6.1	(12)	5.1	(10)	1.5	(3)	54.3	(107)	85.8 ± 2.1
Eared grebe	1988	GL	290	5.9	(17)	1.0	(3)	5.2	(15)	9.7	(28)	9.7	(28)	.7	(2)	31.7	(92)	74.0 ± 1.3
Eared grebe	1989	GL	136	11.0	(15)	1.5	(2)	2.9	(4)	0	(0)	5.9	(8)	0	(0)	21.3	(29)	78.8 ± 2.0

[1] Includes all eggs from nests monitored to hatching or failure.

[2] Eggs that contained dead embryos that were not abandoned prior to estimated hatch dates were assumed to have died of embryo toxicosis.

[3] Some addled eggs in which fertility was not detected might have contained undeveloped embryos.

[4] Eggs that could have been removed from nests by predators or knocked out of nests by adults; exact fate of eggs are unknown.

[5] Eggs that persisted past maximum estimated hatch dates but were not collected or examined.

[6] Includes random and nonrandom eggs collected and analyzed for selenium.

exceeded 8 $\mu g/g$ dry weight except for eggs from Canada geese in 1989. At the Kendrick area, egg hatchability in successful nests was less than 90 percent in aquatic birds except for American avocets and eared grebes at Goose Lake in 1989 (table 27). When nests with embryo toxicosis are included, egg hatchability ranged from 45.1 percent to 86.2 percent in all species during both years. If selenium was not a factor, nests with embryo toxicosis likely would have been successful. Therefore, egg hatchability from combined successful and embryo-toxic nests could be compared to egg hatchability in successful nests from uncontaminated populations.

Chick survival also appeared reduced in aquatic birds at the Kendrick area, particularly in American avocets and eared grebes. No live avocet chicks were observed at Rasmus Lee and Goose Lakes in 1988, and only 10 (11 percent of eggs presumed hatched excluding viable eggs collected) were observed in 1989. Six dead avocet chicks were found on nesting islands at Rasmus Lee Lake but were too decomposed for necropsy.

In 1988, only 10 juvenile grebes were observed at Goose Lake, which represents 9 percent of the eggs presumed hatched. In 1989, 77 juvenile grebes were observed; however, a relation could not be made between the number of juvenile grebes and the percentage of eggs presumed hatched because only a sample of nests was monitored.

Chick loss comparable to that found at the Kendrick area was observed at Kesterson among eared grebes in 1983 and in 1984 and 1985 among American avocets (Ohlendorf and others, 1986a). Prefledging brood mortality was estimated to approach 100 percent among avocets at Kesterson (Williams and others, 1989). Selenium concentrations in aquatic invertebrate samples collected at Rasmus Lee and Goose Lakes typically eaten by avocets and grebes (table 16) exceeded dietary selenium concentrations that reduced duckling survival in mallards. Mallard hens fed concentrations of selenium as selenomethionine of 8 or 16 $\mu g/g$ dry weight produced ducklings exhibiting reduced growth and survival (Heinz and others, 1989). This suggests that selenium contamination probably accounted for most of the chick mortality in American avocets and eared grebes nesting at Rasmus Lee and Goose Lakes in 1988 and 1989.

Canada Goose

Comparisons with uncontaminated populations indicate that Canada geese at Rasmus Lee Lake suffered reproductive impairment. Selenium contamination in Canada geese has not been reported previously in the literature. Poor hatching success resulted primarily from embryo mortality in Canada geese. Several studies have associated selenium contamination with similar effects in other species of aquatic birds (Hoffman and others, 1988; Hoffman and Heinz, 1988; Ohlendorf and others, 1986a, 1986b, and 1989; Skorupa and Ohlendorf, 1991). Other factors that might cause poor hatching success and high rates of embryo death were not observed or detected in Canada geese at Rasmus Lee Lake.

The deformities found in Canada goose embryos at the Kendrick area are unusual. Although many studies of Canada goose reproduction have examined embryos, no deformities have been reported in the literature (Bellrose, 1980). Two deformed goose embryos were found, however, at Ouray in Utah. Selenium

Table 27.--Estimated egg hatchability of successful and combined (successful and embryo toxic) aquatic-bird nests and mean selenium concentrations in eggs from Rasmus Lee and Goose Lakes during 1988 and 1989

[Concentrations in micrograms per gram; S.E., standard error; --, no value available]

Species, site, and type	Year	Sample sizes: Nests[2]	Sample sizes: Eggs[3]	Eggs presumed hatched[4]	Egg failures: Deformed embryos[5]	Egg failures: Dead embryos	Egg failures: Undeveloped[6]	Egg failures: Unknown[7]	Hatchability: Percent	Hatchability: ± S.E.	Selenium concentrations in eggs[1]: Geometric mean ± S.E.
Canada goose											
Rasmus Lee Lake											5.51 ± 0.26
Successful	1988	8	37	27	1	5	4	0	77.1	± 13.1	
Combined		13	56	27	1	17	11	0	47.4	± 13.4	
Rasmus Lee Lake											9.80 ± 0.82
Successful	1989	12	67	56	0	10	1	0	82.6	± 8.00	
Combined		22	107	56	0	40	11	0	45.1	± 9.95	
American avocet											
Rasmus Lee Lake											68.4 ± 5.78
Successful	1988	7	24	15	0	4	2	3	63.1	± 9.77	
Rasmus Lee Lake											85.8 ± 2.10
Successful	1989	28	98	76	3	8	10	1	79.8	± 5.06	
Combined		44	152	76	9	43	22	2	50.8	± 6.67	
Goose Lake											--
Successful	1988	1	2	1	0	0	1	0	50.0	0	
Goose Lake											--
Successful	1989	3	11	11	0	0	0	0	100.0	0	

Table 27.--Estimated egg hatchability of successful and combined (successful and embryo toxic) aquatic-bird nests and mean selenium concentrations in eggs from Rasmus Lee and Goose Lakes during 1988 and 1989--Continued

Species, site, and type	Year	Sample sizes: Nests[2]	Sample sizes: Eggs[3]	Eggs presumed hatched[4]	Egg failures: Deformed embryos[5]	Egg failures: Dead embryos	Egg failures: Undeveloped[6]	Egg failures: Unknown[7]	Hatchability: Percent	Hatchability: ± S.E.	Selenium concentrations in eggs[1]: Geometric mean ± S.E.
Eared grebe											
Goose Lake											74.0 ± 1.32
Successful	1988	65	138	112	1	6	5	14	85.3	± 3.11	
Combined		74	152	112	1	16	6	17	74.9	± 4.25	
Goose Lake											78.8 ± 2.01
Successful	1989	53	118	104	2	8	1	3	91.0	± 2.69	
Combined		56	124	104	2	13	2	3	86.2	± 3.76	

[1]Includes random and nonrandom eggs collected and analyzed for selenium.

[2]Does not include abandoned nests, nests with incomplete observations, or nests in which all eggs appeared infertile.

[3]Does not include eggs missing prior to minimum estimated hatching dates or viable eggs collected.

[4]Eggs that disappeared during possible hatching dates and eggs known to hatch.

[5]Most deformed embryos were dead when collected.

[6]Addled eggs with no discernable embryonic development. Fertility impossible to determine.

[7]Eggs that persisted past maximum hatching dates, but were not collected or examined.

concentrations of 2.5 and 3.0 μg/g dry weight in the two deformed goose embryos from Ouray were similar to those found in deformed goose embryos from Rasmus Lee Lake (2.4 and 4.4 μg/g dry weight)(Bruce Waddell, U.S. Fish and Wildlife Service, oral commun., 1991).

The highest percentage of Canada goose egg losses at Rasmus Lee Lake in 1988 and 1989 was attributed to embryo toxicosis (table 26). Embryo mortality in geese occurred more frequently at Rasmus Lee Lake than in uncontaminated populations that normally experience less than 10 percent embryo mortality (Collias and Jahn, 1959; Hanson and Browning, 1959; Hanson and Eberhardt, 1971; Klopman, 1958; Miller and Collins, 1953; Steel and others, 1957; and Vermeer, 1970).

Hatchability of Canada goose eggs at Rasmus Lee Lake was less than 90 percent in 1988 and 1989, the percentage reported for normal populations (Klopman, 1958, p. 181)(table 27). However, observer disturbance may have contributed to reduced egg hatchability in Canada geese in 1988. Klopman (1958, p. 181) reported that egg hatchability of wild geese normally approaches 90 percent. Brakhage (1965, p. 767) reviewed several studies of wild geese and reported egg hatchability ranged from 83 to 93 percent.

Although egg hatchability in Canada geese was not significantly different (Kruskal-Wallis significance level = 0.9) between years, geometric mean selenium concentration in eggs was significantly larger (Kruskal-Wallis significance level <0.005) in 1989 than in 1988. These results indicate that impaired egg hatchability and teratogenesis might occur in Canada goose populations with geometric mean concentrations of selenium in eggs as small as 5.5 μg/g dry weight (tables 24 and 27).

Canada goose hatching success at Rasmus Lee Lake in 1988 appeared above average (table 28); however, the estimate is inflated because viable eggs were collected randomly from 71 percent of the nests. Buss and Wing (1966, p. 26) estimated a 73 percent nest success for Canada geese, and Bellrose (1980, p. 161) reported an average nest success of 70 percent. In contrast, Canada goose hatching success at Rasmus Lee Lake was only 52 percent in 1989 when viable eggs were collected randomly from 26 percent of the nests.

Factors usually contributing to poor hatching success in wild geese were not observed at Rasmus Lee Lake. Poor hatch success in wild geese has resulted from human disturbance (Culbertson and others, 1971, p. 232-233; McCabe, 1979, p. 121-122), social factors (Collias and Jahn, 1959, p. 502 and 508), predation or desertion (Geis, 1956, p. 419), pesticide (heptachlor) effects (Blus and others, 1984, p. 1097), and flooding (Combs and others, 1984, p. 230 and 233). Desertion was observed at Rasmus Lee Lake in only one goose nest in both 1988 and 1989. Crowding, flooding, and predation were not observed, although two eggs disappeared prior to estimated hatch dates in 1988. Eggs missing prior to estimated hatch dates could have been removed from nests by predators or knocked out of nests by adults, but the exact fate of these eggs is unknown. All goose nests were on islands separated by water that would deter most mammalian predators. A few California gulls (Larus californicus) frequented the area, but other avian predators were uncommon. Moreover, nest destruction, broken eggshells, or predator sign were not observed. The only pesticide residue detected in Canada goose eggs was p,p'-DDE. One of six goose eggs analyzed contained a detectable concentration (0.01 μg/g wet weight) of p,p'-DDE, which was much less than concentrations that impaired reproduction in brown pelicans (3 μg/g wet weight)(Blus, 1982).

Table 28.--Estimated maximum hatching success of aquatic bird eggs and of nests monitored at Rasmus Lee and Goose Lakes and mean selenium concentrations in eggs during 1988 and 1989

[Concentrations in micrograms per gram; RL, Rasmus Lee Lake; GL, Goose Lake]

Species	Location	Year	Eggs hatched[1]		Nest in which eggs hatched[2]		Selenium concentrations in eggs[3]
			Percent	Sample size[4]	Percent	Sample size[5]	Geometric mean
Canada goose	RL	1988	51	72	93	14	5.5
		1989	50	125	52	27	9.8
American avocet	RL, GL	1988	68	34	89	9	68.4
		1989	47	197	64	55	85.8
Eared grebe	GL	1988	69	290	90	107	74.0
		1989	79	136	88	59	78.8

[1]Viable eggs collected and eggs that disappeared during estimated hatch dates were considered as hatched.

[2]Nests in which at least one egg was presumed hatched or in which a viable egg was collected.

[3]Random and nonrandom eggs collected and analyzed for selenium.

[4]Eggs from nests monitored to hatching or failure (maximum estimated hatch dates).

[5]Nests monitored to hatching or failure (maximum estimated hatch dates).

Canada geese at Rasmus Lee Lake suffered reproductive impairment at smaller geometric mean concentrations of selenium than other species of aquatic birds. Other factors appeared insufficient to explain the poor reproductive success in Canada geese. To eliminate other factors, however, controlled laboratory studies of selenium contamination in Canada geese would be required.

American Avocets

Reproductive effects in American avocets at Rasmus Lee Lake were similar to those observed at other selenium-contaminated sites such as Kesterson and the Tulare Basin in California. Most notably, malformed and undeveloped avocet embryos were observed in 1989 at Rasmus Lee Lake. Avocets at Rasmus Lee Lake also suffered high rates of embryo mortality, which resulted in poor hatching success.

In 1989 at Rasmus Lee Lake, 24 percent of the avocet embryos examined were grossly malformed (table 24). In 1988, no embryo malformations were found in avocets, but only two were examined. In 1989, frequencies of malformations in avocet embryos from Rasmus Lee Lake (table 24) were similar to those of other selenium-contaminated areas. Whereas, in an uncontaminated population of avocets at Volta (Hoffman and others, 1988, p. 520), no abnormal embryos were observed. In the Tulare Basin, at the West Farmers site, 24 percent of the avocet embryos examined were deformed; at Peck Pond 27 percent were deformed. The mean selenium concentration in eggs for avocets nesting at the West Farmers site was 60 μg/g dry weight and at Peck Pond, 66 μg/g dry weight (Joseph P. Skorupa, U.S. Fish and Wildlife Service, oral commun., 1991). The geometric mean selenium concentrations in eggs for avocets at Rasmus Lee Lake was greater than 60 μg/g dry weight in both 1988 and 1989 (table 24).

No malformed embryos were observed in avocet nests in 1988 at Rasmus Lee and Goose Lakes, but only eight nests were monitored. The frequency of embryo malformations in avocet nests at the Kendrick area in 1989 (table 25) was 12 percent less than the maximum reported for Kesterson. The maximum frequency of embryo deformities in avocet nests reported for Kesterson was 18.2 percent (Ohlendorf, 1989, p. 161).

The frequency of dead avocet embryos observed at Rasmus Lee Lake (table 25) exceeded both those at the uncontaminated Volta site and those found at a selenium-contaminated site at Kesterson. Avocet embryo mortalities occurred in 2 percent of nests and in less than 1 percent of eggs at Volta (Hoffman and others, 1988, p. 520). At Kesterson, the largest frequency of avocet embryo mortality reported was 18.2 percent in nests monitored during 1985 (Ohlendorf, 1989, p. 161). At Kesterson, the largest mean selenium concentration in avocet eggs reported was 32.2 μg/g dry weight in 1985 (Ohlendorf and Skorupa, 1989, p. 324). Geometric mean selenium concentrations in avocet eggs at Rasmus Lee Lake in 1988 and 1989 (table 25) were more than double that found at Kesterson.

Higher selenium concentrations in avocet eggs at Rasmus Lee Lake might explain the greater incidence of dead embryos. Ohlendorf and others (1986b) found the probability of embryo toxicosis (dead or deformed embryos) in avocets increased as selenium concentration in eggs increased. If the rate of necrosis increases with increasing selenium concentrations in the tissues, death of the embryo could preclude the development of gross malformations. To assess this possibility, histological examinations of embryos at earlier stages of development would be required.

Geometric mean selenium concentrations in avocet eggs at Rasmus Lee Lake were greater than 8 μg/g (table 27), the threshold associated with reduced hatchability and impaired embryo viability in American avocets (Skorupa and Ohlendorf, 1991). Embryo toxicosis was the largest cause of avocet egg loss (table 26) and resulted in poor egg hatchability at the Kendrick area. In contrast, embryo toxicosis was not observed for avocet eggs at Volta and hatchability was 100 percent during three years (1983 to 1985)(Ohlendorf and others, 1989, p. 794). Egg hatchability in avocets (Recurvirostra spp.) averages 91 to 99 percent in uncontaminated populations (Joseph P. Skorupa, U.S. Fish and Wildlife Service, written commun., 1991). At Rasmus Lee Lake, avocet egg hatchability was less than 91 percent in 1988 and 1989 (table 27).

In American avocets, nest success was 25 percent lower, and geometric mean selenium concentrations in eggs were 20 percent greater in 1989 than in 1988 (table 28). In addition, nest success in avocets during 1989 was much lower than that reported for uncontaminated populations. Sidle and Arnold (1982, p. 78) reported 88 percent nest success for avocets at Mud Lake, North Dakota, where nest predation did not occur. Grover and Knopf (1982, p. 145-147) reported 83 percent nest success for avocets that lost nests to coyote predation and flooding. Other reports attributed poor nest success in avocets to predation (Chase Lake)(Sidle and Arnold, 1982, p. 78) and to a combination of flooding, predation, and desertion (Ohlendorf and others, 1989, p. 793). No evidence of nest predation or abandonment in avocets was observed at Rasmus Lee or Goose Lakes. However, 12 eggs that might have been removed by predators or knocked out of nests by adults were missing prior to estimated hatch dates in 1989. Fewer eggs were presumed hatched in monitored avocet nests in 1989 than 1988 (table 28). However, in both years avocet egg success at Rasmus Lee Lake was less than expected (79 to 90 percent of avocet eggs hatched) for uncontaminated avocet populations where predation was minor (Gibson, 1971, p. 452; and Sidle and Arnold, 1982, p. 78, Mud Lake).

Geometric mean selenium concentration in avocet eggs at Rasmus Lee Lake was significantly larger (Kruskal-Wallis significance level <0.01) in 1989 than 1988. This corresponds with the detection of embryo malformations, increased embryo mortality, and decreased hatching success during 1989. Egg hatchability, however, was not significantly different (Kruskal-Wallis significance level = 1.0) between 1988 and 1989. Geometric mean selenium concentrations in avocet eggs were large enough to impair egg hatchability (greater than 8 μg/g dry weight) and to cause teratogenesis (greater than 13 μg/g dry weight) in both years.

Eared Grebes

Reproductive effects associated with selenium contamination were identified in eared grebes from Goose Lake. Malformed and undeveloped embryos were observed in eared grebes. In addition, grebes suffered impaired egg hatchability. Adverse impacts at Goose Lake, however, were not as apparent as those reported for grebe populations at other selenium-contaminated sites.

The frequencies of malformations in eared grebes at Goose Lake exceeded those associated with uncontaminated populations but did not exceed those found at other selenium-contaminated sites. At Goose Lake, 6 percent in 1988 and 12 percent in 1989 of all eared grebe embryos examined were grossly malformed (table 24). No abnormal embryos were observed in an uncontaminated eared grebe population at Volta (Hoffman and others, 1988, p. 520). At a selenium-contaminated site in the Tulare Basin, 40 percent of the eared grebe embryos examined were deformed (Joseph P. Skorupa, U.S. Fish and Wildlife Service, oral commun., 1990). Thirty percent of the eared grebe embryos examined from Kesterson had deformities (Roger L. Hothem, U.S. Fish and Wildlife Service, oral commun., 1991). The frequencies of abnormal embryos or chicks at Kesterson were 15.6 percent in nests (Ohlendorf, 1989, p. 161) and 5.5 percent in eggs (Ohlendorf and others, 1986a, p. 52). Frequencies of malformations in monitored grebe nests and eggs at Goose Lake (table 25) were lower than at Kesterson; however, chicks were not included in results at Goose Lake. Only two eared grebe chicks were found in monitored nests at Goose Lake. One young eared grebe with a deformed bill was found dead in the nesting area in 1989 and may have come from a monitored nest. Perhaps other malformed chicks were missed that hatched between nest visits.

The frequency of embryo death was greater in eared grebes at Goose Lake (table 25) than at Volta where no dead grebe embryos were found (Hoffman and others, 1988, p. 520). However, embryo mortality occurred less frequently in eared grebes at Goose Lake than at Kesterson (Hoffman and others, 1988, p. 520; Ohlendorf and others, 1986a, p. 52). The frequency of embryo or chick mortality in grebe nests at Kesterson was 60 percent (Hoffman and others, 1988, p. 520; Ohlendorf, 1989, p. 161; Ohlendorf and others, 1986a, p. 52). The frequency of embryo mortality in grebe nests at Goose Lake was substantially lower (table 25) than that found at Kesterson. However, the frequency of chick mortality was not assessed in grebes at Goose Lake. Circumstantial evidence at Goose Lake indicates that more embryo deaths occurred in monitored grebe nests than were recorded. Grebe nests disintegrated rapidly and unidentified eggs were found floating in the nest area.

Ohlendorf and others (1986b) found that embryo toxicosis was not related significantly to selenium concentration in eared grebes, because even the smallest selenium concentrations in eggs from Kesterson (44 μg/g dry weight) exceeded the embryo-toxic concentration. The probability of embryo toxicosis in grebes at Kesterson was 84 percent and remained constant with respect to selenium concentrations in eggs. Ninety-eight percent of the eared grebe eggs from Goose Lake contained selenium concentrations equal to or greater than 44 μg/g dry weight. Therefore, the probability of embryo toxicosis presumably would be similar for eared grebes at Goose Lake (84 percent).

Despite less frequent embryo toxicity in grebes from Goose Lake, geometric mean selenium concentrations in grebe eggs (table 25) were greater than those reported for other selenium-contaminated sites (Ohlendorf and Skorupa, 1989, p. 321). The mean selenium concentration in eggs was 69.7 μg/g dry weight for randomly collected grebe eggs at Kesterson (Ohlendorf and others, 1986b, p. 333). Mean selenium concentration for random and nonrandom eggs was 23 μg/g dry weight in grebes from the Tulare Basin (Joseph P. Skorupa, U.S. Fish and Wildlife Service, oral commun., 1990).

Differences in the concentration of different forms of selenium in dietary items between selenium-contaminated sites might explain differences in the frequencies of embryo toxicity. Dietary items usually contain about 80 percent organoselenium (Joseph P. Skorupa, U.S. Fish and Wildlife Service, oral commun., 1991). Organic forms of selenium are more toxic to aquatic birds than inorganic forms (Heinz and others, 1987 and 1988; Hoffman and Heinz, 1988). Eared grebes from Goose Lake might consume organisms that contain higher proportions of inorganic selenium. Organisms with firm outer surfaces, such as mollusks (Mollusca), usually contain more inorganic selenium than other grebe food items (Joseph P. Skorupa, U.S. Fish and Wildlife Service, oral commun., 1991). Separate selenium concentrations in the yolk and albumen could indicate the proportion of inorganic to organic content in the egg (Joseph P. Skorupa, U.S. Fish and Wildlife Service, oral commun., 1991), but yolk and albumen from egg samples from the Kendrick area were not analyzed separately.

Hatchability of successful eared grebe nests at Goose Lake was less than 91 percent in 1988 (table 27). Egg hatchability in grebes (Podicipedidae) normally approaches 91 percent (Joseph P. Skorupa, U.S. Fish and Wildlife Service, written commun., 1991). Although hatchability of successful nests did not appear to be reduced in 1989, embryo toxicosis was the main loss of eared grebe eggs at Goose Lake in 1989 (table 26). When grebe nests with embryo toxicosis are included, egg hatchability was less than 91 percent in 1988 and 1989 (table 27). Egg hatchability in successful grebe nests did not differ significantly between 1988 and 1989 (Kruskal-Wallis significance level = 1.0). Similarly, selenium concentrations in eggs did not differ significantly between years (Kruskal-Wallis significance level = 0.1). Geometric mean selenium concentrations in grebe eggs were large enough to expect impaired egg hatchability (>8 μg/g dry weight) in both years (Skorupa and Ohlendorf, 1991).

Maximum hatching success of eared grebe nests and eggs is presented in table 28. Intensive searches were made to mark all grebe nests at Goose Lake in 1988, and 88 percent of the nests found were monitored to hatching or failure. Observer activities in 1988 might have affected grebe production. Therefore, observer activities were curtailed in 1989; nest success for eared grebes was 2 percent less and egg success was 10 percent greater in 1989. In both years, eared grebe nest success at Goose Lake was larger than the estimated 82.3 percent for eared grebes at Kesterson (Ohlendorf and others, 1986b, p. 335).

The results of this study probably underestimate embryo death and inflate hatching success in eared grebes. Circumstantial evidence indicates some eared grebe eggs that disappeared during estimated hatch period, and were presumed hatched, might have failed. Some nonviable eggs found floating in the nesting area likely came from monitored nests but were not included in results. Eight floating eared grebe eggs were collected in 1988, of which three contained dead late-stage embryos. In 1989, 28 floating eggs were collected; all contained dead late-stage embryos, of which 2 were malformed. To assess the effects of selenium contamination on eared grebe reproduction accurately, precise timing of nest monitoring visits and laboratory incubation of sample eggs would be necessary.

Bioaccumulation

Bioaccumulation is the uptake of elements or compounds by organisms from water and food. Bioaccumulation can occur only if uptake of an element by an organism exceeds rate of elimination (Rand and Petrocelli, 1985). Several biological, chemical, and physical processes cycle selenium into and out of water, sediment, and biota. Selenium is mobilized by oxidation and methylation of inorganic and organic selenium by plant roots and micro-organisms, direct uptake and burrowing activities of benthic invertebrates, detrital uptake by fish and wildlife, and chemical oxidation associated with currents, wind, stratification, and precipitation (Lemly and Smith, 1987).

Selenium concentrations in the food chain at the Kendrick area were generally one or more orders of magnitude greater than concentrations of this element in water (fig. 39). The largest selenium concentration in biota occurred in Rasmus Lee and Goose Lakes, which also had the largest selenium concentrations in water and sediment. Geometric mean selenium concentrations in biota samples from Rasmus Lee and Goose Lakes were 900 to 3,000 times

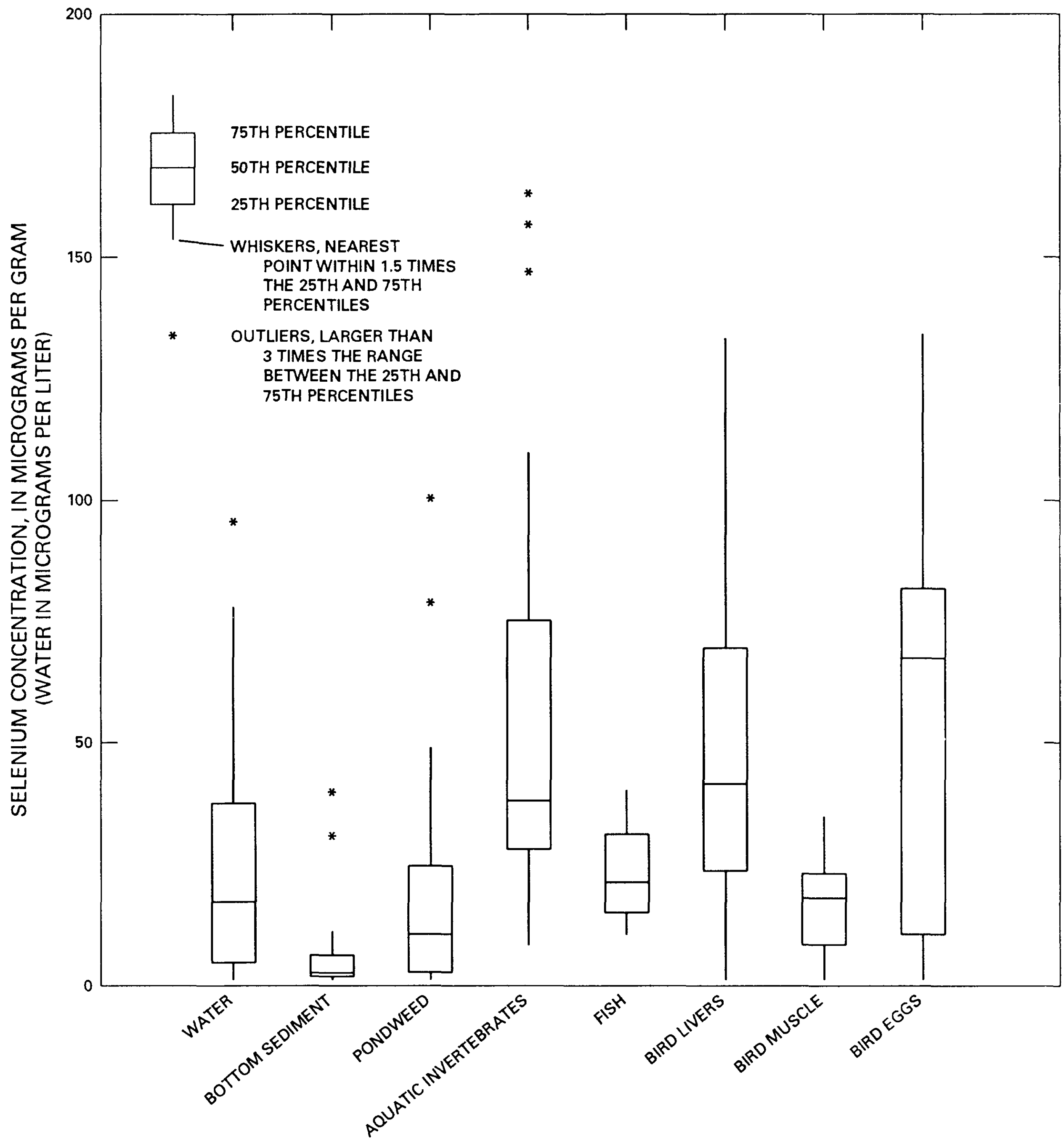


Figure 39.--Selenium concentrations in samples of water, bottom sediment, and biota.

greater than median selenium concentrations in water. Excluding aquatic vegetation from Goose Lake, geometric mean selenium concentrations in samples of the food chain from Rasmus Lee and Goose Lakes were 2 to 18 times greater than geometric mean selenium concentrations in samples of the bottom sediments. The geometric mean selenium concentration in samples of aquatic vegetation from Goose Lake was smaller than that in samples of the bottom sediment. Geometric mean selenium concentrations in samples of aquatic vegetation from Thirtythree Mile Reservoir and Illco Pond were also smaller than geometric mean selenium concentrations detected in samples of the bottom sediment. At Oxbow Pond, the geometric mean selenium concentration in samples of aquatic vegetation was almost equal to that detected in samples of the bottom sediment. This is to be expected because sediment acts as a sink for selenium. Natural evaporation contributes to large selenium concentrations in water, sediment, and biota through bioaccumulation from Rasmus Lee and Goose Lakes because they are both closed-basin systems.

Samples of aquatic invertebrates and fish from Illco Pond had geometric mean selenium concentrations almost three times greater than the concentrations detected in samples of the bottom sediment. At Thirtythree Mile Reservoir, the geometric mean selenium concentration in samples of aquatic invertebrates was almost six times that detected in samples of bottom sediment. The geometric mean selenium concentration in samples of fish collected from Thirtythree Mile Reservoir was almost eight times that detected in samples of bottom sediment. Geometric mean selenium concentrations in samples of biota from Thirtythree Mile Reservoir, Illco Pond, and Oxbow Pond were 200 to 13,400 times larger than the median selenium concentrations in water samples from these sites.

Of all the biota at the Kendrick area, geometric mean concentrations of selenium in samples indicated that aquatic vegetation accumulated the smallest concentrations of selenium and that aquatic invertebrates accumulated the largest concentrations of selenium. Chironomids, in particular, accumulated the largest geometric mean selenium concentrations of all the biota sampled in the Kendrick area, about 4,000 times the median selenium concentration in the surface-water samples.

Although samples of aquatic invertebrates from Oxbow Pond contained the smallest geometric mean selenium concentration in the study area, the geometric mean selenium concentration was 13,000 times larger than the median selenium concentration in the surface-water samples collected at Oxbow Pond. The geometric mean selenium concentration in aquatic vegetation from Oxbow Pond was 2,700 times larger than the median concentration detected in water samples from that site.

Livers and eggs from resident aquatic breeding birds collected at Rasmus Lee and Goose Lakes contained geometric mean selenium concentrations from 900 to 2,100 times larger than median selenium concentrations in the water samples from these sites. In addition, aquatic birds that spend a few weeks during spring migrations at the Kendrick area wetlands could accumulate enough selenium to threaten reproduction even after they have moved on to other sites. Birds feeding at selenium-contaminated sites can accumulate large concentrations of selenium in livers quickly. Mallards fed a diet containing selenium concentrations of 10 μg/g wet weight (12.5 μg/g dry weight) took only 7 to 8 days to reach 95 percent of peak liver concentrations (Heinz and others, 1990). Although elimination of one-half the selenium concentrations in mallard livers took only 19 days, selenium concentrations in livers did not decrease to control concentrations until after 71 days.

At Rasmus Lee and Goose Lakes selenium concentrations in mallard diet items ranged from 3.3 μg/g dry weight (table 16) to 166 μg/g dry weight (table 17). During onsite experiments conducted at Ouray in Utah, where selenium concentrations in water were elevated, the mean selenium concentration in livers of captive mallards increased from 2.8 μg/g to 27 μg/g dry weight within 1 week of exposure. Of the 50 captive mallards released, only 1 adult male survived 4 weeks of exposure. Selenium concentration in the adult male mallard liver was 106 μg/g dry weight. Concentrations of selenium in mallard diet items ranged from 9.7 to 63 μg/g dry weight at Ouray (Bruce Waddell, written commun., 1991). Therefore, mallards stopping over at the Kendrick area could accumulate excess selenium in 1 week that could threaten their reproductive success at other uncontaminated areas if egg laying occurs soon thereafter. Similar effects are also likely with other aquatic bird species. Heinz and others (1990) determined that mallards accumulated adverse selenium concentrations of 30 μg/g dry weight in 1 week, but it took 2 to 3 weeks for the birds to eliminate the selenium.

Rasmus Lee and Goose Lakes are common stopover sites for migratory birds in this semi-arid country. Goose Lake, in particular, contains high densities of aquatic vegetation and invertebrates, as well as shallow water depths that make these food sources readily available to aquatic birds. Aquatic invertebrates are an important dietary component for nesting hens (Swanson, 1984), and they pose a large selenium-exposure risk to female waterfowl nesting in the study area or stopping over en route to northern breeding grounds. Additionally, in some species of waterfowl, prenesting hens increase feeding time threefold, adding to the exposure risk at the Kendrick area. Aquatic birds can accumulate adverse concentrations of selenium in body tissues or eggs by feeding in a heavily contaminated area for 1 or 2 weeks (U.S. Fish and Wildlife Service, 1990). Additionally, large selenium concentrations in bird livers can cause a decrease in body weight.

The effects of selenium on fish and wildlife are not restricted to the wetlands in the Kendrick area. Several creeks convey selenium-contaminated drainwater from the project area into the North Platte River, contributing to bioaccumulation of selenium in the trout fishery. Impacts from these drainages appear to be cumulative as selenium concentrations in water and rainbow trout increase downstream. Selenium in rainbow trout downstream from the irrigation-drainwater inflows to the North Platte River is present at concentrations suspected of adversely affecting reproduction. Although fish accumulate selenium by consuming contaminated food, such as aquatic invertebrates, they also may uptake this element directly from the water (Hodson and others, 1980; Hodson and Hilton, 1983; Lemly, 1982).

SOURCES OF SELENIUM

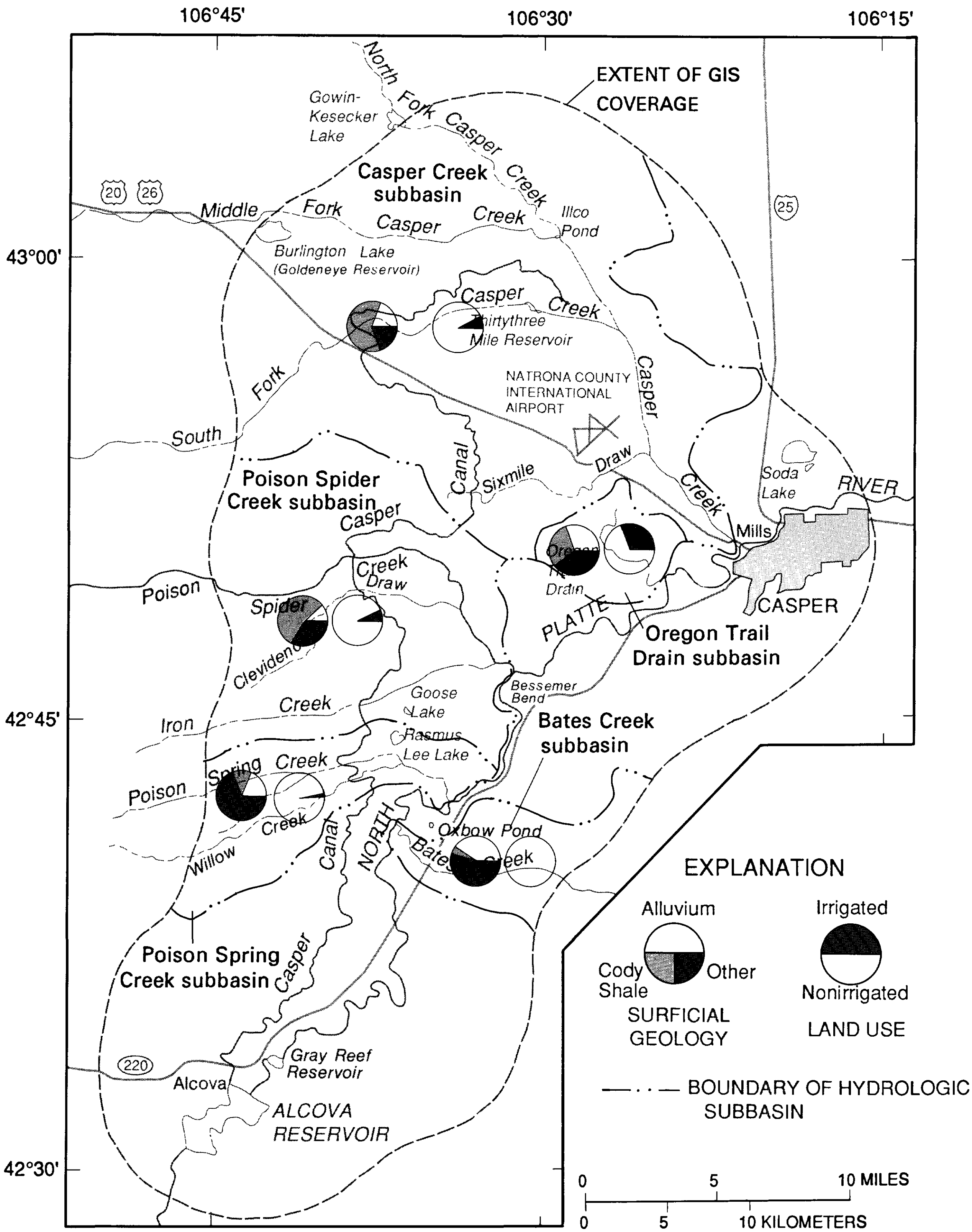
A geographic information system (GIS) was used as an analytical tool to assist in the development of a regression model that will help to identify and to assess those factors that have the greatest potential to explain selenium discharge from the Kendrick area. This analysis covers an area defined by Crist (1974, p. 3-4) that was slightly smaller than the study area for the rest of this report, because the area mapped by Crist (1974) was less extensive. The extent of the GIS study area and the boundaries of hydrologic subbasins selected for this analysis are shown in figure 40.

The GIS was used to produce and display a variety of maps and tables used to evaluate spatially distributed data. GIS techniques were used to determine values of independent variables for use in a stepwise multiple-regression analysis. The development of a model that identifies and assesses potential selenium contamination areas could assist in the evaluation of factors contributing to selenium discharges from the Kendrick area.

Several other studies have linked land use factors to water quality. Duckson (1989) and Hren and others (1984) used statistical approaches to evaluate large data sets and to correlate the effects of land-use activities on water quality in coal-mining areas. Gilliland and Baxter-Potter (1987) used a GIS to predict water-quality problems associated with nonpoint-source agricultural pollution.

The detailed information and data presented in this report were examined to determine factors that might contribute to selenium contamination of water resources in the Kendrick area. Map features in the GIS study area were digitized, and physical characteristics and selenium concentrations associated with the map features were stored with the digitized data in the GIS. Geology was digitized from Crist (1974) (fig. 3). Soil developed on Quaternary alluvium had a similar range of total soil selenium concentrations as soil developed on Cody Shale (fig. 5) and areas of Quaternary alluvium are assumed to be derived from Cody Shale. Irrigated areas were digitized from maps revised in 1982 by the Casper-Alcova Irrigation District for an application for amended appropriations for water rights (fig. 1). Boundaries of hydrologic subbasins (fig. 40) were determined using USGS 1:100,000 scale topographic maps of the area. Lengths of streams were determined from USGS digital line graphs from 1:100,000 scale maps (U.S. Geological Survey, 1985). Irrigation water-delivery canals (fig. 17) were digitized from 1:48,000 engineering maps provided by the U.S. Bureau of Reclamation.

Some irrigated land has been reported in that part of the Bates Creek subbasin in the study area for this analysis; however, water is diverted from Bates Creek and its tributaries and not from the Casper Canal. Water rights for irrigated fields in the Bates Creek subbasin tend to be junior to other water rights along the North Platte River, and often no irrigation water is available. During the period of this study (1988-90) when irrigation water was available, it was generally only for short periods during the early part of the season (George Davis, U.S. Soil Conservation Service, oral commun., 1990; Randy Tullis, Wyoming State Engineer's Office, oral commun., 1991). For the purposes of this study, area of irrigated land in the part of the Bates Creek subbasin in the study area used for this analysis has been estimated at 0 acres, and therefore, length of irrigation canals and ditches also is estimated at zero.



Base modified from U.S. Geological Survey 1:100,000 digital line graph map series: Casper, 1979; and Midwest, 1981
Universal Transverse Mercator projection

Figure 40.--Relative distribution of geologic formations and irrigated and nonirrigated land for selected hydrologic subbasins.

The GIS was used to store map features such as areas (irrigated land and geology), lines (irrigation canals and streams), and points (soil, plant, and water sampling points), along with physical characteristics and selenium concentrations of the GIS study area. Characteristics of spatial features such as areas of irrigated land or length of streams were computed and stored by the GIS. Selenium concentrations at the sampling sites were added manually and stored by the GIS.

A series of overlay, merging, and extraction procedures was used to complete spatial analysis of the physical characteristics and selenium concentrations of the study area for this analysis. Areas of spatial features, lengths of linear features, and point data for specific areas were extracted for selected hydrologic subbasins, and the results were analyzed using stepwise multiple-regression techniques.

Selenium discharge, areas of irrigated soil overlying Cody Shale and alluvium derived from Cody Shale, length of streams, total length of irrigation-water delivery canals, and other measured variables listed in table 29, were aggregated using the GIS. This was accomplished by digitally overlaying the sampling sites as identified in figures 7, 8, 17, and 22, with the five subbasin boundaries. During this operation, the GIS automatically annotated the sampling-sites attribute data with the identity of the subbasin in which each site was located, and thus allowed the aggregation of the data. Tabular data files were then generated by the GIS. These data were analyzed and summary statistics were calculated for measured independent variables in each of the subbasins (table 29).

A regression model was developed using median selenium discharges during 1988 from each subbasin as a dependent variable regressed on measured physical and chemical characteristics of the hydrologic subbasins as the independent variables. The physical characteristics consisted of areas of soil overlying Cody Shale and of soil overlying alluvium derived from Cody Shale (areas that have been identified as having the largest total selenium concentrations in soil), length of streams, irrigation-water delivery canals, and area of irrigated land (table 29). Chemical characteristics consisted of total selenium concentrations in soil, plant, and water samples.

Several relations exist between median selenium discharges in streams and the independent variables. Median selenium discharges in streams and a drain from subbasins in the study area increase as the area of irrigated land in the subbasin increases (fig. 41). In addition, median selenium discharges in streams from the subbasins tend to be larger from those basins with larger median selenium concentrations in ground water (fig. 42).

Median selenium discharge is correlated with total area and area of Cody Shale or alluvium derived from Cody Shale. When irrigated land is considered as a percentage of total subbasin area (fig. 43), median selenium yield increases with increasing percentage of the total subbasin area that is irrigated, indicating that irrigated area, and not total area of the subbasin, controls selenium yields. Irrigation appears to provide the water necessary to move selenium from the Kendrick area. Precipitation in the study area is insufficient to produce effective percolation and leaching of selenium through soil in the study area (Larsen, 1951).

Table 29.--Summary statistics for part of selected hydrologic subbasins in the study area

[kg/d, kilograms per day; µg/g, micrograms per gram; µg/L, micrograms per liter; --, not determined]

Subbasin in study area for this analysis (fig. 40)	Median selenium discharge (kg/d)	Irrigated area (acres)	Total area (acres)	Area of Cody Shale (acres)	Area of Quaternary alluvial deposits (acres)	Length of irrigation canals (miles)	Length of perennial streams (miles)
Casper Creek	2.61	12,300	146,800	88,810	29,630	120	92
Oregon Trail Drain	.85	3,160	10,230	2,970	3,210	17	7.4
Poison Spider Creek	1.96	5,610	71,070	39,440	8,330	50	38
Poison Spring Creek	.36	583	26,190	3,090	5,110	14	19
Bates Creek	.13	0	15,814	780	6,420	0	18

Subbasin in study area for this analysis (fig. 40)	Median total selenium concentration and, in parentheses, number of samples (µg/g dry weight)			Median selenium concentration and, in parentheses, number of samples		
	Nonirrigated soils	Irrigated soils	Big sagebrush	(µg/g dry weight) Alfalfa	(µg/L) Ground water	(µg/L) Drainwater
Casper Creek	0.37 (14)	0.60 (51)	0.20 (13)	1.20 (50)	25.5 (36)	13.5 (18)
Oregon Trail Drain	-- --	.20 (12)	-- --	.70 (12)	17.5 (40)	7.3 (12)
Poison Spider Creek	.30 (20)	.30 (26)	.40 (19)	.71 (26)	50.0 (25)	4.3 (12)
Poison Spring Creek	.10 (14)	.45 (6)	.35 (13)	1.60 (6)	10.0 (6)	8.0 (5)
Bates Creek	.60 (1)	-- --	.40 (1)	-- --	20.0 (4)	-- --

Total selenium discharges generally increase with increasing total selenium concentrations in soil (fig. 44). Bates Creek subbasin had the smallest amount of irrigated area (assumed to be 0 acres in this study), but also had one of the largest median concentrations of total selenium in soil samples (0.60 µg/g). An increase in irrigation in the Bates Creek subbasin would likely increase the selenium discharge from the basin.

Constraints existed on the number of variables that could be included in the model because of the small number of subbasins for which median selenium discharges in streams could be estimated. Because the total number of independent variables was larger than the number of median selenium discharges, the statistical software available for regression analysis could not perform all possible regressions; stepwise regression was used as an alternative.

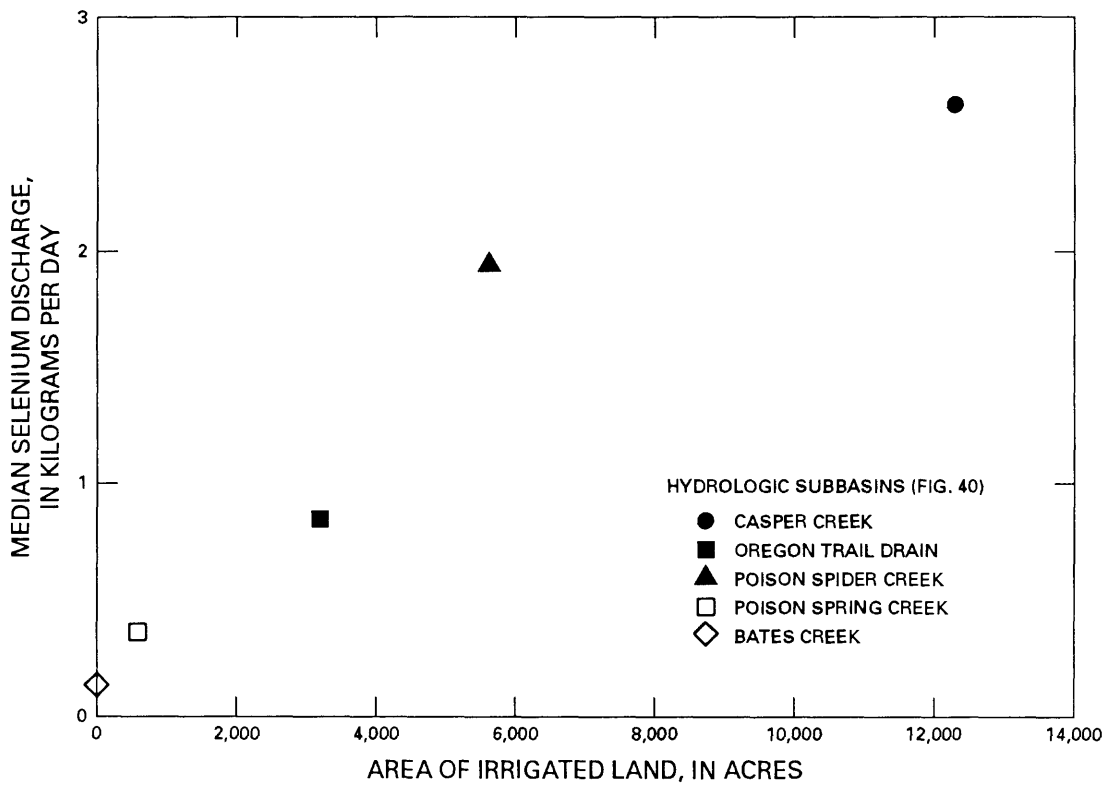


Figure 41.--Median selenium discharge as a function of area of irrigated land.

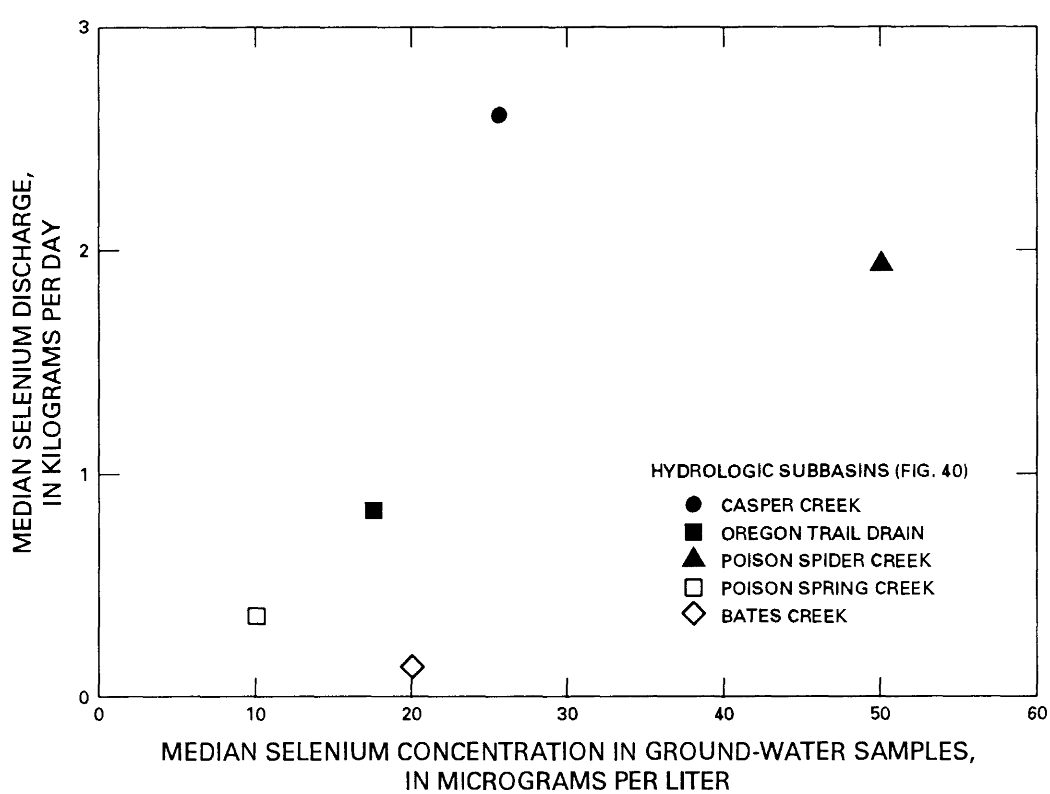


Figure 42.--Median selenium discharge as a function of median selenium concentration in samples of ground water.

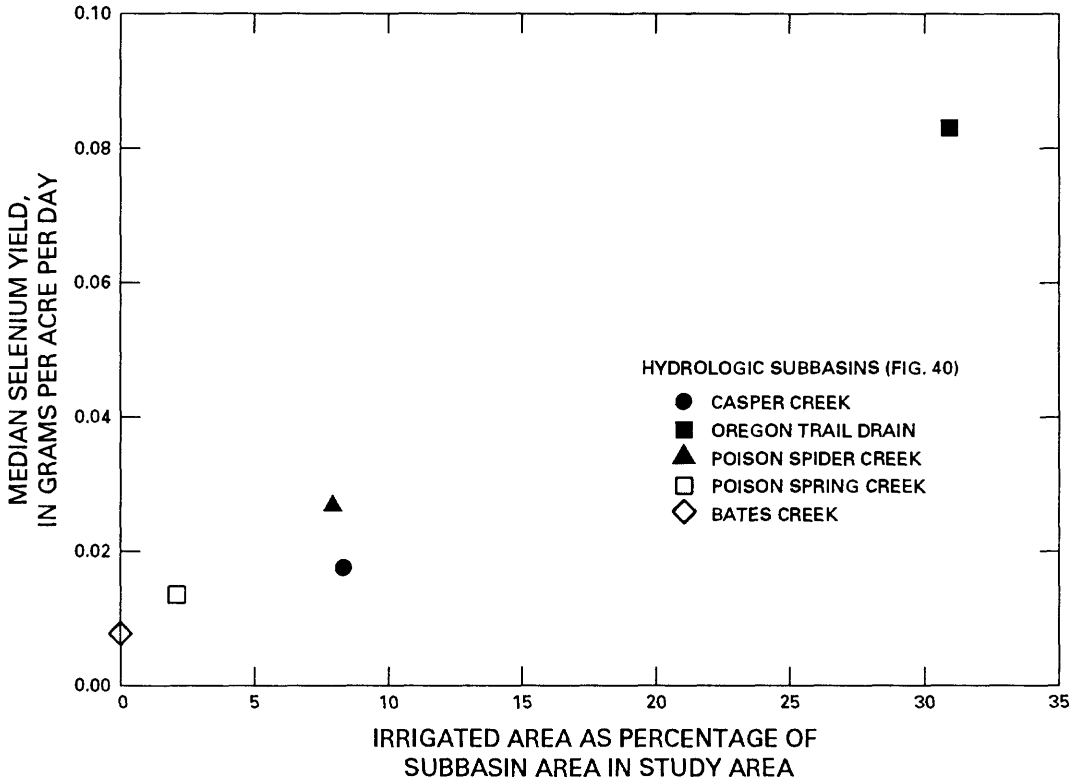


Figure 43.--Median selenium yield as a function of irrigated area as a percentage of subbasin area in the study area for this analysis.

Each of the measured independent variables (table 29) was evaluated using a stepwise multiple-regression analysis. The largest amount of variability ($R^2 = 0.99$, F significance = 0.01) in median selenium discharges was explained by the following model:

Median selenium discharge = 0.18 (area of irrigated land, in acres) + 19.3 (median selenium concentration in ground water, in micrograms) - 76

Using this model, predicted selenium yield was then calculated for each square mile land section (640 acres) in the study area of this analysis. The predicted selenium yield from an individual section is a function of the extent of irrigated land and the median selenium concentration in ground water in that section. The potentials for contributing selenium to tributaries of the North Platte River from each section of the Kendrick area are shown in figure 45.

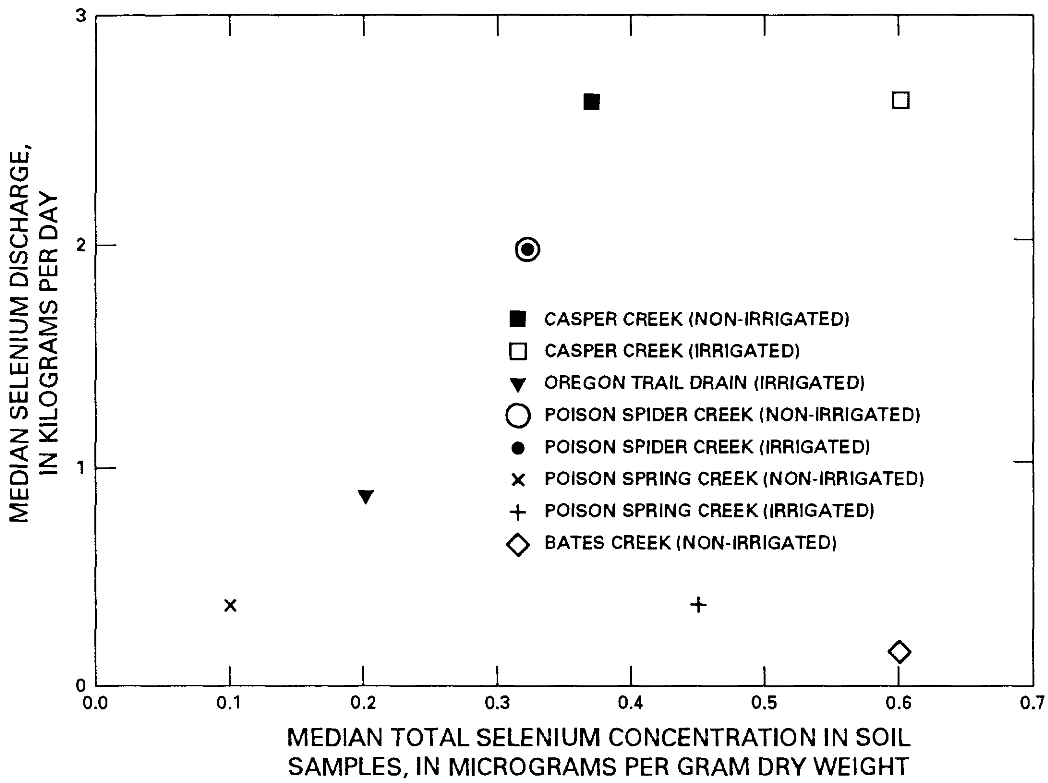


Figure 44.--Median selenium discharge as a function of median total-selenium concentrations in soil samples.

The regression results indicate that the irrigation intensity (as measured by area of irrigated land) and concentrations of selenium in ground water are responsible for a large part of the selenium discharge from sub-basins. The range of total selenium concentrations in soil from the study area is within the 95th percentile range of total selenium concentrations in soils in the Northern Great Plains (fig. 5); however, irrigation appears to increase weathering of minerals containing selenium and to leach selenium from the soil. Seasonal changes in soil moisture, caused by irrigation, create changing reduction/oxidation conditions in the soil profile. These changing soil conditions affect the solubility, transport, and subsequent accumulation of selenium.

The results from the regression model indicate that a decrease in the irrigated area or changes in irrigation practices might decrease the selenium discharges in tributaries to the North Platte River. Irrigation might contribute to increased selenium concentrations through evapoconcentration and leaching of selenium from the soil profile. Although soil and plant data were not used in the final regression model, these data were useful for locating areas of large selenium concentrations in the study area.

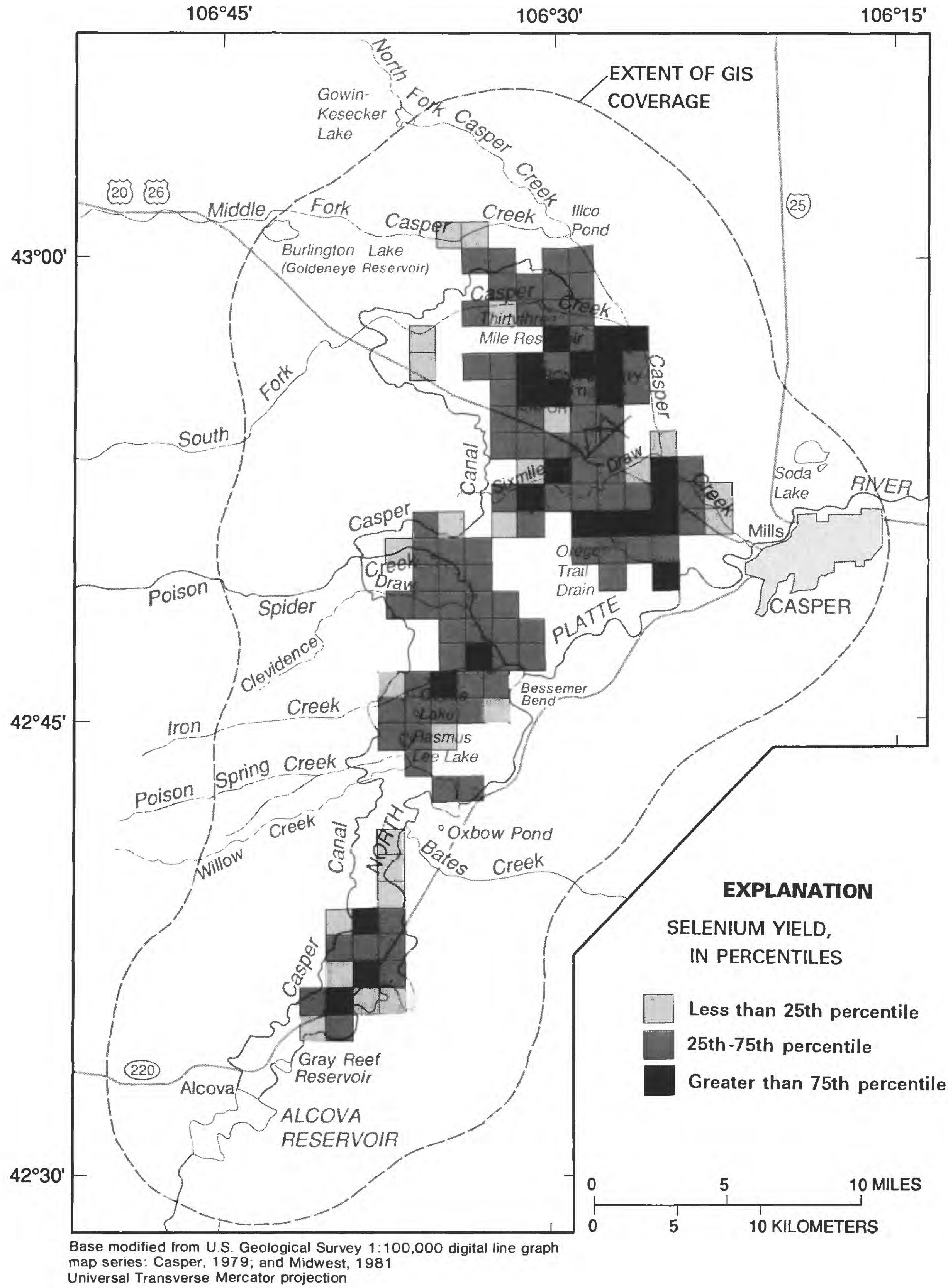


Figure 45.--Predicted selenium yields of potential areas for contributing selenium to the North Platte River.

SUMMARY AND CONCLUSIONS

The Kendrick Reclamation Project area (Kendrick area) in Natrona County, central Wyoming, has been studied as part of the U.S. Department of the Interior Irrigation Drainage Program to address water-quality problems related to irrigation drainage. Forage crops are the most important crops in the Kendrick area and about 20,000 of 24,000 irrigable acres are harvested annually. The North Platte River and the alluvium along the river are sources of water for domestic and industrial supplies, as well as for municipal water supplies for Casper and adjacent communities. The Kendrick area includes several wetlands that provide habitat for aquatic birds and other wildlife.

This report describes the extent, magnitude, effects, and exposure pathways of selenium associated with irrigation drainage on water resources and biota. Trace elements and constituents other than selenium were evaluated but, except for arsenic, boron, cadmium, mercury, and lead in selected biological samples, were not assessed to be at concentrations harmful to wildlife or humans. The specific objectives of this report, and the fulfillment of objectives, are discussed in the following summary:

1. Describe the magnitude and distribution of selenium in irrigated and nonirrigated soil and representative plants in and adjacent to the Kendrick area.

In response to earlier findings of large concentrations of selenium in the study area, two detailed geochemical surveys were conducted in 1988 to study the distribution of selenium in soil (0-3.3 ft depth), big sagebrush, and alfalfa. A survey of the nonirrigated rangeland focused on soil overlying specific geologic units as possible sources of selenium, and a survey of the irrigated agricultural lands assessed the extent of selenium mobilization, transport, and concentration in the irrigated areas.

All of the nonirrigated soil samples contained total selenium concentrations less than the 3.3 $\mu g/g$ baseline range established for soil samples from the Northern Great Plains. The geometric mean (0.64 $\mu g/g$) and range (less than 0.1 to 2.1) of selenium concentration was largest for soil overlying Cody Shale.

In contrast to selenium concentrations in nonirrigated soil samples, selenium concentrations in about 20 percent of the big sagebrush samples exceeded the 1.1 $\mu g/g$ dry weight baseline range established for this species in the West. Compared to nonirrigated soil, selenium concentrations tended to be larger in big sagebrush collected from areas underlain by the Cody Shale. A total of 13 big sagebrush samples from 6 of the 13 geologic units exceeded the 1.1 $\mu g/g$ dry weight baseline range established for big sagebrush in a study of the western United States.

Analysis-of-variance and grid-sampling designs were used to define the lateral and vertical variation of selenium concentrations in samples of irrigated soil. Selenium concentrations were not significantly different among soil depth zones but were significantly different laterally. Therefore, using the grid data, the total and water-extractable soil selenium maps reliably show the distribution of selenium concentrations across the landscape. Only two of about 200 samples of soil from irrigated fields contained total selenium concentrations slightly larger than the concentration of 3.3 $\mu g/g$ dry weight upper baseline established for soil from the Northern Great Plains.

Large differences in selenium concentrations were detected in samples of alfalfa from different fields and in the same field in the Kendrick area. Alfalfa samples from about 15 percent of the irrigated fields contained selenium concentrations in excess of about 4 μg/g dry weight (up to 25 μg/g dry weight), which is the concentration above which selenium is reported to be potentially hazardous to livestock if consumed for prolonged periods. However, no documented incidences of selenosis have occurred in the study area. Most of these alfalfa samples were concentrated in an area of 11 contiguous sections west of the Natrona County Airport, where samples of selenium-enriched surface water and drainwater also were collected. The irrigated soil samples just to the north of this seleniferous area contained concentrations of total selenium as large as 3.2 μg/g. The cause for this displacement of a large zone of seleniferous alfalfa from a possible source area of slightly seleniferous soil might be because of ground-water flow patterns in this area. Evaporation in an associated area of ground-water depression could explain the large selenium concentrations of the zone.

2. Describe the magnitude and distribution of selenium in water from the North Platte River and its tributaries, irrigation drainwater, and in water and bottom sediment in wetlands.

Selenium concentrations in surface water and bottom sediment samples were assessed to determine concentrations and sources of selenium in water resources in the study area. Virtually all selenium in streams of the area was present as dissolved selenium. Only a small amount of selenium was transported as suspended selenium, even during spring runoff.

Selenium concentrations in water samples from the North Platte River ranged from less than the reporting limit of 1 μg/L to 10 μg/L. Selenium concentrations in the North Platte River generally increased in the downstream direction. All selenium concentrations in water samples from the North Platte River were less than the current MCL for drinking water of 10 μg/L, with the exception of one sample containing 10 μg/L, collected downstream of the city of Casper.

The selenium concentration in the North Platte River could be toxic to fish through bioaccumulation. The 4-day average Federal freshwater aquatic life criterion of 5 μg/L for selenium was exceeded (5.2-6.0 μg/L) five times during a 50-day monitoring period in 1989.

The tributaries draining the Kendrick area receive nearly all of their selenium from the Kendrick area. All eight samples from Poison Spring Creek upstream from the Kendrick area contained selenium concentrations less than the reporting limit of 1 μg/L, compared to a median concentration of 92 μg/L in Poison Spring Creek downstream of the Kendrick area.

During 1988, the major tributaries flowing into the North Platte River from Alcova Reservoir to Casper accounted for an average of 52 percent of the total selenium discharge measured at the North Platte River site downstream of Casper. The Casper Creek drainage basin, which contains the largest selenium anomaly identified in the soil-, plant-, and irrigation drainwater-sampling programs, contributed the largest measured selenium discharge (2.61 kg/d) of the five tributary sites during the monitoring period.

Irrigation drainwater, which consists of a combination of shallow ground water and excess irrigation water that flows across the surface of fields during irrigation, was sampled during June and August 1988. Drainwater samples had statistically larger selenium concentrations during June (median 10 μg/L) than during August (median 5 μg/L). Flushing of salts containing large concentrations of selenium from soil occurs during spring and early summer irrigation.

Selenium concentrations were monitored at six wetlands in and adjacent to the Kendrick area. Water samples collected at the four wetlands in or near the Kendrick area contained dissolved selenium concentrations greater than the 5 μg/L Federal freshwater aquatic life criterion for selenium. The median dissolved-selenium concentrations were largest in Rasmus Lee Lake (38 μg/L) and Goose Lake (54 μg/L). The median dissolved-selenium concentrations in water samples from two wetlands outside the Kendrick area and not affected by irrigation drainage, were equal to or less than 1 μg/L.

Six sampling sites had selenium concentrations in bottom sediment exceeding 4 μg/g dry weight, a level of concern for fish and wildlife. The largest concentrations of selenium in bottom sediment were detected in samples from Goose Lake (20 to 43 μg/g). In the reducing conditions characteristic of bottom sediment, selenium might be expected to accumulate.

3. Describe the seasonal variability in selenium loading to the North Platte River from the major irrigation-drainwater discharges and how these discharges affect the concentration of selenium in river water used as a municipal supply by the city of Casper.

Drainwater samples collected during June had a statistically larger selenium concentration than samples collected during August 1988. Larger values of specific conductance and larger concentrations of selenium, magnesium, sodium, and sulfate in samples collected during June indicate that salts accumulated in the soil since the previous irrigation season are flushed from the soil by irrigation water applied during the early part of the irrigation season.

Water samples collected intermittently at the outlet of Oregon Trail Drain since 1968 contained the smallest selenium concentrations during July through August. The largest selenium concentrations in water samples collected from November through May could be the result of an increased percentage of ground water in irrigation drainwater samples. During the summer months, application of irrigation water dilutes selenium concentrations in the drainwater.

Selenium concentrations generally increased in the downstream direction in water samples from the North Platte River. All selenium concentrations in water samples from the North Platte River were less than the current MCL for drinking water of 10 μg/L, with the exception of one sample containing 10 μg/L, collected downstream of the city of Casper.

4. Describe the magnitude and distribution of selenium in shallow ground-water and surface-water sources in the Kendrick area that are used as domestic or livestock water supplies.

Selenium concentrations in ground water were evaluated from analyses of water samples collected from 117 wells and 5 springs during 1968-70 and from 51 domestic wells during 1988. Ground-water samples containing selenium concentrations larger than the 75th percentile range (140 μg/L) were collected from wells near other wells that yielded water samples containing selenium concentrations less than 10 μg/L, indicating the large spatial variability in ground-water selenium concentrations. The quality of ground water sampled is affected by the depth at which casing intervals of wells are open, geologic formations, and seasonal fluctuations. Well-permit files maintained by the Wyoming State Engineer list 481 wells primarily used for domestic purposes and 202 wells primarily used for stock purposes. Because of the large variability in selenium concentrations in ground water, it is difficult to estimate how many of the domestic-use wells might have concentrations of selenium greater than recommended levels for various uses.

5. Describe the principal geochemical processes that affect the concentration of selenium in surface water and ground water and identify the important geochemical processes controlling selenium mobility.

The process of evaporation and natural runoff affect selenium concentrations in water from wetlands and ground water in the Kendrick area. On the basis of the ratios of selenium and chloride concentrations in water samples from Rasmus Lee and Goose Lakes (closed-basin systems), the large selenium concentrations could have been derived by evaporation of irrigation water delivered by the Casper Canal, without leaching of soluble forms of selenium from soil or rocks. Water samples from Thirtythree Mile Reservoir and Illco Pond (flow-through systems) showed considerable enrichment in selenium compared to concentrations approximated by the evaporative-concentration line, presumably caused by leaching and desorption of selenium from soil and rock. The oxygen-18/oxygen-16 and deuterium/hydrogen isotopic ratios in water samples from Rasmus Lee and Goose Lakes were shifted to the right of the continental precipitation line, confirming the substantial effect evaporation has on the large selenium concentrations at these sites. The oxygen-18/oxygen-16 and deuterium/hydrogen isotopic ratios of water samples from Thirtythree Mile Reservoir and Illco Pond indicate limited effects of evaporative concentration, confirming leaching and desorption of selenium from soil and rock in the Kendrick area.

A plot of selenium and chloride concentrations in irrigation drainwater samples was used to evaluate the significance of evaporation in affecting selenium concentrations. Samples of irrigation drainwater from the Kendrick area plot above the evaporative concentration line. This enrichment of selenium indicates that most of the selenium observed in the irrigation drainwater samples is derived by leaching or desorption of soluble forms of selenium from soil and rocks during irrigation, rather than evaporation.

Intensive monitoring at Rasmus Lee Lake during 1988 detected increases in total (dissolved plus suspended) selenium concentrations in water samples collected, as large as 1,000 μg/L, during snowmelt in late winter and in early spring. The increase in selenium concentrations could have been caused by a variety of factors, including turbulence affecting bottom sediment, changes in redox state of the water, or dissolution of selenium-rich salts along the shore of Rasmus Lee Lake. The migratory aquatic birds using the Kendrick area wetlands during the late winter and early spring could accumulate increased concentrations of selenium. Onsite studies conducted in Utah demonstrated significant selenium accumulation within 1-week periods by captive-raised mallards.

Six bottom-sediment samples contained selenium concentrations in both the less than 63-μm and less than 2 mm-size fractions that were larger than the 4 μg/g dry weight concentration established as a level of concern for fish and wildlife. The largest concentrations of selenium in bottom sediment were detected in samples from Goose Lake (20 to 43 μg/g dry weight). The reducing environment of bottom sediment could result in selenium enrichment.

6. Describe the aquatic bird use of wetland areas.

The Kendrick area serves as an important spring and fall stopover for migratory birds and also provides nesting habitat for a few species of waterbirds including: Canada geese, American avocets, eared grebes, mallards, blue-winged teals, and gadwalls. Peak numbers of waterbirds were observed during late August and September. The abundance and diversity of migratory waterbirds attracted to wetlands in the Kendrick area have serious implications from the standpoint of exposing avian fauna to concentrations of selenium exceeding the 5 μg/L criterion for the protection of freshwater aquatic organisms.

7. Describe the selenium concentrations in aquatic vegetation, aquatic invertebrates, fish, and aquatic birds; and evaluate whether concentrations could have potentially adverse physiological effects on fish, aquatic birds, or humans who regularly consume fish and aquatic birds.

Biota inhabiting the closed-basin systems (Rasmus Lee and Goose Lakes) accumulated larger concentrations of selenium than biota inhabiting flow-through systems (Thirtythree Mile Reservoir and Illco Pond). The large selenium concentrations in water samples from Rasmus Lee and Goose Lakes also were indicated in the aquatic-bird food chain at these sites. Selenium concentrations in pondweed samples collected from Rasmus Lee Lake (13.0 - 104 μg/g) and Goose Lake (3.3 - 28 μg/g) greatly exceeded the dietary threshold of 3 μg/g dry weight for aquatic birds. Selenium concentrations in pondweed samples from Thirtythree Mile Reservoir (0.1 - 2.8 μg/g) and Illco Pond (2.4 - 7.6 μg/g) were less than, to slightly greater than, the 3 μg/g dry weight dietary threshold concentration. These wetlands had smaller selenium concentrations in water samples than did Rasmus Lee or Goose Lakes. Geometric mean selenium concentrations in aquatic-invertebrate samples from Rasmus Lee and Goose Lakes were from 2.7 to 14 times larger than selenium concentrations in aquatic-invertebrate samples collected from other wetlands in the Kendrick area. Aquatic birds nesting at the Kendrick area contained selenium concentrations in liver samples (as much as 94.2 μg/g dry weight) and eggs (as much as 135 μg/g dry weight) larger than concentrations suspected of causing adverse reproductive effects.

Poor egg-hatchability (less than 90 percent), embryo mortality, and deformities associated with large selenium concentrations (7.5 to 13 μg/g dry weight) were observed in Canada goose, American avocet, and eared grebe eggs. Geometric mean selenium concentrations in eggs were greater than background (3 μg/g dry weight) in Canada geese (7.5 μg/g dry weight), American avocets (82.7 μg/g dry weight), and eared grebes (75.1 μg/g dry weight). Geometric mean selenium concentrations were larger than those known to impair egg hatchability and to cause teratogenic effects in American avocets and eared grebes. Large geometric mean selenium concentrations also were detected in samples of livers from juvenile Canada geese (35.6 μg/g dry weight), adult American avocets (75.9 μg/g dry weight), and adult and juvenile eared grebes

(74.2 and 77.7 μg/g dry weight) at concentrations that could impair reproduction or cause mortality (greater than 30 μg/g dry weight). Selenium toxicosis was diagnosed as a possible cause of death for one bird carcass and might have contributed, along with other factors, to the deaths of other birds observed in the study area.

As the Kendrick area wetlands continue to attract nesting aquatic birds that feed on diet items with large concentrations of selenium, reproductive losses likely will continue. In addition to Canada geese, American avocets, and eared grebes, other aquatic birds that nest in the Kendrick area might suffer reproductive impairment. Rasmus Lee and Goose Lakes are the primary nesting sites for aquatic birds, but reproductive losses associated with selenium contamination probably occur at other wetland sites in the Kendrick area.

The potential for aquatic bird production at the Kendrick area is small relative to the Central Flyway as a whole; however, birds nesting outside the Kendrick area might use the area wetlands for feeding. A diversity of waterbirds nest nearby at Soda Lake; they might feed in the Kendrick area wetlands and accumulate large selenium concentrations.

8. Describe the major food-chain pathways for bioaccumulation of selenium in selected fish and aquatic birds.

Selenium concentrations in the food chain at the Kendrick area were larger than this element in water. Aquatic invertebrates had geometric mean selenium concentrations almost three to six times greater than the concentrations found in the bottom sediment. Selenium concentrations in the food chains in both the flow-through and closed-basin wetlands were above thresholds known to cause adverse effects on fish and aquatic birds.

The selenium-contaminated food chain threatens resident breeding birds and migratory birds stopping in the Kendrick area to rest and feed. The aquatic birds could accumulate substantial concentrations of selenium from the Kendrick area, possibly enough to cause adverse reproductive effects. Rasmus Lee and Goose Lakes are attractive stopover sites for migratory birds in this semiarid country. Goose Lake, in particular, contains an abundance of aquatic vegetation and invertebrates as well as shallow water depths that make these food sources easily available to aquatic birds. Aquatic invertebrates are an important dietary component for nesting hens. Aquatic invertebrates from the Kendrick area provide enough selenium to threaten reproduction not only in female aquatic birds nesting in the Kendrick area, but also those stopping over en route to northern breeding grounds. Additionally, in some species of aquatic birds, prenesting hens increase feeding time threefold, adding to the exposure risk at the Kendrick area.

9. Describe the major sources of selenium and factors contributing to selenium discharge from the Kendrick area.

A geographic information system was used as an analytical tool to assist in the development of a regression model that will help to identify and to assess areas that have the greatest potential to contribute selenium to water resources in the Kendrick area. Physical characteristics and selenium concentrations in soil, plant, and water samples were evaluated as factors contributing to selenium discharge from selected hydrologic subbasins in and near the Kendrick area. Physical characteristics included areas of geologic formations, amount of irrigated land, and lengths of irrigation canals in selected hydrologic subbasins.

Each of the measured independent variables was considered, using a step-wise regression analysis. The area of irrigated land and median selenium concentration in ground-water samples in each basin are the most important factors in explaining the variability of median selenium discharges.

The results of the regression model indicate that a decrease in irrigated area or changes in irrigation practices might decrease the selenium discharges in tributaries to the North Platte River. The net effect of increased area of irrigated land is to increase selenium concentrations through evaporative concentration and leaching of selenium from the soil, thus increasing the selenium discharge in tributaries to the North Platte River.

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